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ANALYSIS OF SOLAR AND WIND ENERGY UTILISATION IN EUROPE AND AFRICA*

Laila Talbi ^{1*}, Mouna Abarkan ², Fatima Ezzahra Saber ³, Ahmed Louardi ⁴,
Jurga Vestertė ⁵, Najiba El Amrani El Idrissi ⁶, Joana Katina ⁷

^{1*,2,3,6}Signals, Systems and Components Laboratory (SSC), Faculty of Sciences and Techniques, Sidi Mohamed Ben Abdellah University, Fez, Morocco

^{1*,2,3,4}Industrial Techniques Laboratory (IT), Faculty of Sciences and Techniques, Sidi Mohamed Ben Abdellah University, Fez, Morocco

^{5,7}Department of Business Technologies & Entrepreneurship, Faculty of Business Management, Vilnius Gediminas Technical University, Vilnius, Lithuania

⁷Institute of Computer Science, Faculty of Mathematics and Informatics, Vilnius University, Didlaukio St. 47, 08303 Vilnius, Lithuania

⁷Faculty of Electronics and Informatics, Vilniaus kolegija / Higher Education Institution, J. Jasinskio st. 15, 01111 Vilnius, Lithuania

E-mails: ^{1*}laila.talbi@usmba.ac.ma (Corresponding author)

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Abstract. The increasing reliance on renewable energy sources is essential for achieving global sustainability, with solar and wind energy playing pivotal roles in mitigating climate change and reducing dependency on fossil fuels. This study presents an in-depth comparative analysis of solar and wind energy utilisation in Europe and Africa, examining the key differences in resource availability, adoption rates, technological advancements, economic factors, and policy frameworks. Europe has made significant progress integrating renewable energy into its energy mix through comprehensive policies, substantial financial investments, and cutting-edge technological developments. In contrast, despite possessing immense renewable energy potential, particularly in solar energy, Africa faces considerable challenges, including inadequate infrastructure, limited funding, and inconsistent policy implementation. The findings highlight the barriers and opportunities for both regions and propose strategies to optimise renewable energy deployment, fostering sustainable development across diverse socio-economic contexts.

Keywords: renewable energy; solar energy; wind energy; Europe; Africa; energy policy; sustainability; technological advancements; energy transition; grid infrastructure

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1. Introduction

The global energy sector is undergoing a fundamental transformation driven by the urgent need to decarbonise economies and expand access to affordable, sustainable energy. Renewable energy—particularly solar and wind—has emerged as a central pillar in this transition. Over the past two decades, Europe has positioned itself as a global leader in renewable energy integration through ambitious climate legislation, technological innovation, and strong market incentives (European Commission, 2020; IEA, 2023). Notably, the EU achieved a 45.3% share of renewables in gross electricity consumption in 2023, the most significant annual increase on record, with wind and solar contributing 38.5% and 20.5%, respectively. As of early 2025, renewables accounted for 47.4% of net electricity generation, reinforcing the EU's role as a frontrunner in clean energy deployment (Statista, 2025).

In contrast, while endowed with exceptional solar and wind resources, many African regions face persistent structural challenges that hinder widespread renewable energy adoption (Chukwu et al., 2022; Anekwe et al., 2024). These include underdeveloped grid infrastructure, high capital investment requirements, inconsistent policy frameworks, and limited access to concessional finance (UNEP, 2021). Sub-Saharan Africa, in particular, remains one of the most energy-poor regions, with more than 550 million people lacking access to electricity as of 2022 (IEA, 2022; Villar-Roldán et al., 2025).

Despite these contrasts, both continents exemplify distinct paths toward renewable energy transition. Europe operates within a highly interconnected, mature energy market, while many African countries are attempting to leapfrog centralised fossil-based systems through decentralised, renewable-based electrification. Crucially, Africa is not a monolithic energy landscape. This study focuses on North, East, and Southern Africa—regions where renewable energy deployment has been most active—to reflect intra-continental diversity in opportunity and constraint.

The primary aim of this study is to conduct a comparative analysis of solar and wind energy utilisation in Europe and Africa, with particular attention to how contextual, institutional, and infrastructural factors influence renewable energy adoption in each region. The study identifies region-specific barriers and enablers by mapping these dimensions, offering insights adaptable to differing socio-economic, geographic, and governance contexts. Doing so contributes to a deeper understanding of how renewable energy transitions can be regionally responsive and globally relevant.

1.1 Analytical Framework

This study employs a tripartite analytical framework grounded in energy transition and governance literature to guide the comparative analysis of renewable energy adoption in Europe and Africa. The framework categorises the determinants of solar and wind energy deployment into three broad but interrelated domains: contextual, institutional, and infrastructural factors. These categories are informed by prior studies in energy systems research, sustainable development, and comparative policy analysis (Sovacool, 2009; Alex-Oke et al., 2025).

Contextual Factors

Contextual factors refer to the environmental, geographic, and socio-economic conditions that shape the technical feasibility and social relevance of renewable energy deployment. These include:

- Solar irradiation and wind speed profiles
- Population distribution and density
- Economic development levels
- Energy access rates and demand patterns
- Regional climate variability and vulnerability

In Europe and Africa, these factors influence the physical viability of renewable technologies and the urgency and design of deployment strategies (Skosana et al., 2023).

Institutional Factors

Institutional factors encompass the policy, legal, and governance structures that support or constrain renewable energy growth. These involve:

- National and regional energy policies
- Political stability and regulatory quality
- Investment incentives, subsidies, and tariffs
- Stakeholder engagement and policy continuity
- Institutional capacity for implementation and monitoring

Institutional strength and alignment are crucial for attracting investment, securing public trust, and ensuring long-term project success (Dube & Horvey, 2023; Muoneke et al., 2023).

Infrastructural Factors

Infrastructural factors relate to the physical and technical systems required for renewable energy generation, integration, and distribution. These include:

- Grid connectivity and reliability
- Energy storage systems
- Transmission and distribution infrastructure
- Access to digital technologies (e.g., smart grids, metering)
- Domestic supply chains and technical expertise

While Europe benefits from well-established energy networks and high grid interconnectivity, many African countries rely on fragmented or non-existent infrastructure, influencing the scale and type of viable renewable projects (Nwaigwe, 2021; Dalla Longa & Zwaan, 2024; Chiki et al., 2025).

2. Renewable energy potential

Solar and wind energy potential differs markedly across Europe and Africa, reflecting variations in geography, climate, and infrastructure (Oxford Institute for Energy Studies, 2021; Chetty et al., 2023; Tachega et al., 2025).

As illustrated in Figure 1, which uses synthesised data to represent general trends based on average global datasets (Global Solar Atlas, 2023), Northern Africa—particularly the Sahara and Sahel zones—has some of the highest levels of solar irradiation globally, often exceeding 2,000 kWh/m² per year.

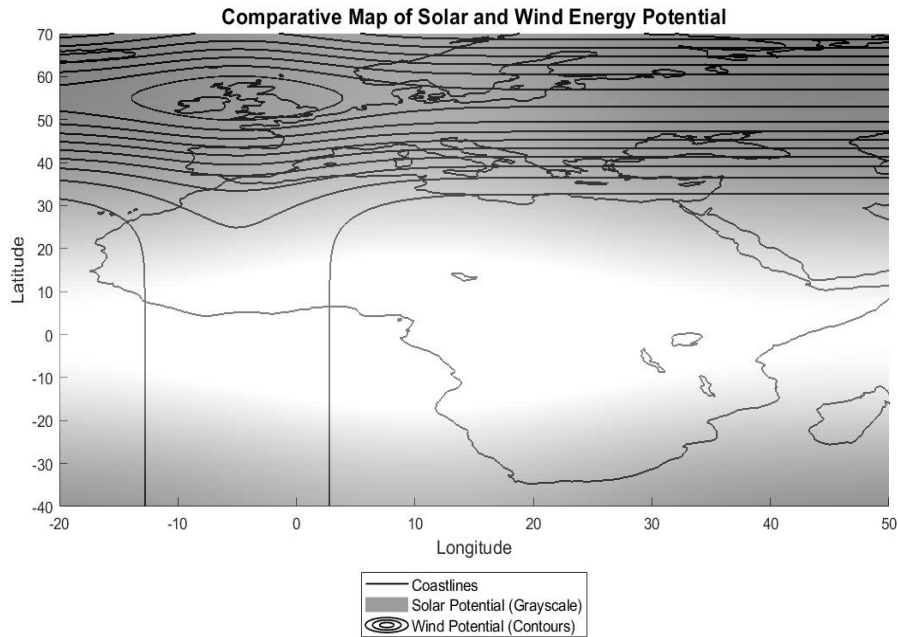


Figure 1. Solar and wind energy potential in Europe and Africa
Source: Generated using synthetic data for visualisation purposes

These values significantly surpass those of Southern Europe, where the most irradiated regions include Spain, Italy, and Greece, averaging between 1,400–1,800 kWh/m²/year (Global Solar Atlas, 2023).

This geographical advantage positions African regions, particularly North and East Africa, as ideal for utility-scale photovoltaic (PV) and concentrated solar power (CSP) installations. Despite this, actual deployment remains limited due to infrastructural, financial, and policy constraints (REN21, 2021; AfDB, 2023).

Wind energy potential shows a different distribution. Europe has substantial wind resources along its northwestern coasts and offshore regions, especially the North Sea, which has become a hub for high-capacity offshore wind farms (IEA, 2023; GWEC, 2023). These regions benefit from consistent wind speeds, shallow water depths, and proximity to industrial demand centres. In Africa, wind resources are promising but more regionally dispersed. High wind zones are concentrated along the Atlantic and Indian Ocean coasts—particularly in Morocco, South Africa, and Kenya—with average wind speeds often exceeding 6 m/s at 100 m height (UNEP, 2021). However, the exploitation of these resources has been slow due to weak transmission infrastructure, limited investment, and policy uncertainty.

These geographic patterns underline the importance of tailoring renewable energy strategies to regional characteristics. While Europe has developed a coordinated, large-scale integration model, many parts of Africa may benefit more from distributed, decentralised renewable energy systems adapted to local contexts.

2.1. Solar Energy Potential

Solar energy potential across Africa is among the highest globally, particularly in the Sahara and Sahel regions, where average annual global horizontal irradiance (GHI) often exceeds 2,000–2,300 kWh/m²/year (Global Solar Atlas, 2023; IRENA, 2022). This makes North and parts of East Africa exceptionally well-suited for both photovoltaic (PV) and concentrated solar power (CSP) installations. Countries such as Morocco, Egypt, and

Namibia have already begun leveraging these conditions, with landmark projects like the Noor CSP complex and Benban Solar Park leading regional development (REN21, 2021; AfDB, 2023).

By contrast, solar potential in Europe is geographically concentrated in the Mediterranean belt, including Spain, Italy, and Greece, with annual irradiance ranging from 1,400 to 1,800 kWh/m²/year (Fraunhofer ISE, 2022). Though lower than in Africa, Europe has achieved high deployment rates through favourable policies, grid reliability, and financing mechanisms. The continent's technological innovation—such as bifacial panels and tracking systems—has helped increase the efficiency of solar capture in less optimal environments (IEA, 2023).

However, while Africa's natural advantage in solar potential is undisputed, technical, economic, and political challenges continue to limit large-scale deployment. These include inadequate transmission systems, limited domestic manufacturing, and uncertainties in policy execution across different countries. As a result, despite its superior solar resource base, Africa contributes only a small fraction of global solar capacity. Moving forward, regional cooperation, cross-border energy markets, and decentralised systems—such as mini-grids and solar home systems—offer promising, context-appropriate solutions (Adom et al., 2025; Adaji et al., 2025).

2.2. Wind Energy Potential

With significant regional disparities, wind energy potential is unevenly distributed across Europe and Africa. Europe's North Sea basin, including coastal areas of Germany, Denmark, and the United Kingdom, has become a global leader in offshore wind deployment thanks to high wind consistency, shallow waters, and strong policy support (GWEC, 2023; European Commission, 2020). Onshore wind is widespread in Spain, France, and Sweden, where long-term planning and public acceptance have facilitated grid integration.

In Africa, wind resources are strongest along coastal regions such as Morocco's Atlantic shore, South Africa's Western Cape, and the Rift Valley regions of Kenya. Wind speeds in these areas often exceed 6.5 m/s at 100m hub height, meeting international thresholds for commercial-scale development (IRENA, 2019; UNEP, 2021). Projects like Lake Turkana Wind Farm (Kenya) and Tarfaya Wind Farm (Morocco) demonstrate the viability of large-scale wind initiatives when supported by political stability and grid access.

Nevertheless, Africa's broader wind development is hindered by high capital costs, grid limitations, and a lack of long-term power purchase agreements (PPAs). In many landlocked or politically unstable countries, bankable projects remain rare. A key difference is that Europe's wind sector benefits from continental coordination and integrated electricity markets, while Africa's is still fragmented. For wind energy to scale in Africa, national efforts must be coupled with regional grid development, standardised regulations, and stronger investor safeguards.

3. Current Adoption and Installed Capacity

As of 2023, Europe and Africa exhibit significant disparities in the adoption of solar and wind energy technologies, both in terms of installed capacity and the degree to which these systems meet regional energy needs (IRENA, 2023; IEA, 2023) (see Figure 2).

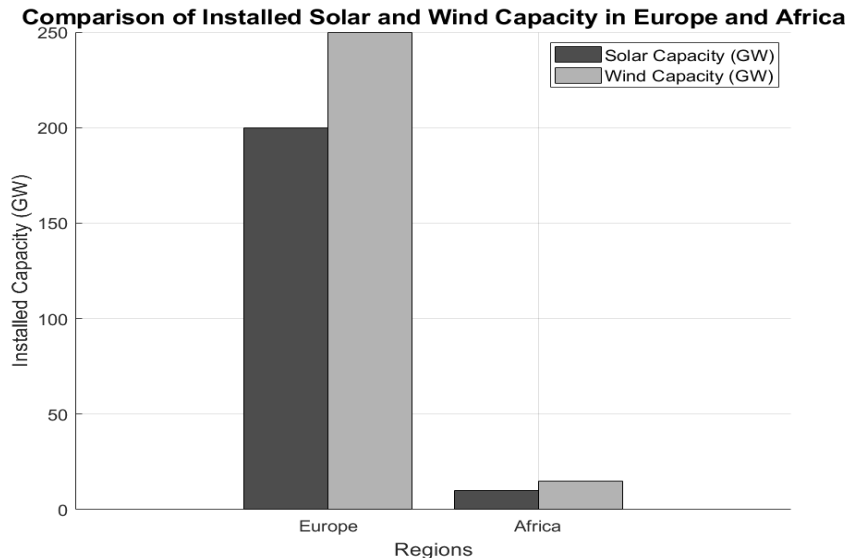


Figure 2. Installed solar and wind capacity in Europe and Africa
 Source: International Renewable Energy Agency (IRENA), 2023.

According to IRENA, Europe accounts for over 640 GW of cumulative renewable energy capacity, with approximately 255 GW from wind and 209 GW from solar. In contrast, Africa has a total installed renewable capacity of around 59 GW, of which solar PV represents just under 12 GW and wind approximately 7 GW (IRENA, 2023).

While these absolute numbers highlight a clear capacity gap, the contrast is more nuanced when considered relative to demand. Europe's high penetration of renewables—particularly in countries like Germany, Denmark, and Spain—has been integrated into existing power systems to displace fossil fuels. For example, Denmark sourced over 50% of its electricity from wind power in 2022 (Danish Energy Agency, 2023). However, most European countries already have near-universal electricity access and mature infrastructure.

The situation differs in Africa: many regions remain energy-poor, and even small-scale renewable projects can have outsized social and economic impacts. Sub-Saharan Africa, where over 550 million people still lack electricity access (IEA, 2022), benefits enormously from decentralised solar mini-grids and off-grid systems. Countries like Morocco, Egypt, and South Africa have made notable progress, with Morocco's Noor Ouarzazate CSP plant and South Africa's REIPPPP wind projects emerging as continental benchmarks (AfDB, 2023; REN21, 2021; Daoudi et al., 2025).

However, other nations—particularly in Central Africa—continue to lag due to limited investment and institutional support.

Figure 2 illustrates the current disparity in installed capacity but does not fully capture the uneven energy access or the different stages of transition. In Africa, capacity expansion must be aligned with decarbonisation goals and broader development priorities such as electrification, energy justice, and rural infrastructure.

4. Infrastructural and Economic Factors

The availability of robust energy infrastructure and access to sustained economic investment has strongly influenced Europe's advancement in renewable energy deployment. Over the past two decades, the region has developed and modernised smart grid systems, expanded high-voltage interconnectors, and built large-scale offshore wind platforms, especially in the North Sea. Countries like Germany, Denmark, and the Netherlands have adopted grid-scale battery storage and digitalised grid management systems to better balance intermittent renewable generation (IEA, 2023; Fraunhofer ISE, 2022). These infrastructural advancements have been reinforced by predictable market instruments—including feed-in tariffs, green bonds, and capacity auctions—reducing investor risk and accelerating private sector engagement (Lazard, 2022; European Commission, 2020).

In contrast, many African countries face substantial infrastructural constraints, particularly in rural or off-grid areas. Challenges such as low electrification rates, outdated or non-existent grid networks, and limited energy storage capacity hinder the integration of utility-scale renewable projects (IRENA, 2022; van der Zwaan et al., 2021).

However, Africa also presents opportunities for leapfrogging traditional grid systems. Innovations such as modular solar mini-grids, mobile pay-as-you-go systems, and community-based energy cooperatives—especially in Kenya, Rwanda, and Ghana—demonstrate how infrastructural decentralisation can support equitable and adaptive energy transitions (IFC, 2021; UNEP, 2021).

Despite the limited scale of Africa's infrastructure, these models have been highly effective in reaching underserved populations and enabling bottom-up energy access. Moreover, international partnerships and multilateral frameworks, such as the African Continental Power Systems Master Plan and cross-border transmission projects under Power Africa, are beginning to address regional infrastructure gaps (AfDB, 2023; African Union Commission, 2021).

From an economic perspective, European countries rely on domestic capital markets and coordinated EU mechanisms. At the same time, African nations remain heavily dependent on foreign direct investment, development finance, and public-private partnerships. This funding asymmetry directly impacts the scope and reliability of infrastructure development and maintenance. It also reflects more profound differences in market maturity and fiscal autonomy. Infrastructural and economic conditions must be understood as mutually reinforcing. Rather than promoting replication of Europe's centralised grid model, policy and investment strategies should prioritise context-responsive infrastructure adapted to each region's energy access needs and financing realities.

5. Institutional and Financial Factors

Institutional and financial structures play a central role in shaping the trajectory of renewable energy deployment across Europe and Africa. These include formal governance mechanisms, regulatory stability, and access to capital, which influences investment flows, policy enforcement, and long-term planning.

In Europe, the energy transition has been supported by robust, regionally coordinated institutional frameworks such as the European Green Deal, the Renewable Energy Directive, and the Fit for 55 packages (European Commission, 2020; IEA, 2023). These initiatives provide clear legislative targets for decarbonisation and ensure alignment among member states. Institutional strength is also reflected in regulatory transparency, monitoring capacity, and long-term policy consistency. Financial instruments such as green bonds, feed-in tariffs, and renewable energy auctions have provided strong price signals, reduced perceived risks, and attracted public and private sector investment (Lazard, 2022; REN21, 2021).

That said, institutional performance in Europe is not uniform. Northern and Western European countries tend to lead in implementation, while Eastern and Southeastern Europe have faced challenges related to institutional fragmentation, weaker regulatory enforcement, and differing national energy priorities (IEA, 2022). Public acceptance of specific technologies (e.g., onshore wind, biomass) also varies, affecting the pace and direction of local transitions.

In Africa, institutional diversity is even more pronounced. While no overarching continental framework is equivalent to the EU, several countries have developed effective national strategies. Examples include Morocco's Integrated Wind and Solar Plan, South Africa's REIPPPP, and Kenya's feed-in tariff and net-metering schemes, which have demonstrated policy innovation and attracted international investment (IRENA, 2022; UNEP, 2021). However, many other African nations struggle with weak institutional capacity, inconsistent policy implementation, and political instability, which often undermine investor confidence and delay project execution (Adebiyi & Moloi, 2024).

A significant divergence between the two continents lies in financial autonomy. Europe's energy transition is primarily financed through internal capital markets, fiscal tools, and EU-wide financial instruments. In contrast, African renewable energy development depends heavily on foreign direct investment (FDI), development aid, and public-private partnerships (AfDB, 2023; IFC, 2021). This dependence introduces volatility, limits local control, and constrains strategic planning, especially in politically or economically fragile states. Additionally, issues like currency risk, regulatory uncertainty, and limited access to affordable long-term credit deter private investors (Pan et al., 2023).

Table 1 summarises the key institutional mechanisms and financial models shaping the renewable energy sectors in Europe and Africa.

Table 1. Institutional and Financial Characteristics of Renewable Energy Development

Region	Institutional Mechanisms	Financial Trends
Europe	- European Green Deal - Renewable Energy Directive - Fit for 55 Package - National Energy and Climate Plans (NECPs) - Coordinated EU policy and regulatory frameworks	- Strong reliance on domestic public and private investment - Use of green bonds, feed-in tariffs, and competitive auctions - Access to EU capital markets and European Investment Bank (EIB) financing - Risk mitigation through stable policy and regulation
Africa	- Renewable Energy Independent Power Producer Programme (South Africa) - Morocco's Solar and Wind Plan - Kenya's Feed-in Tariff and Net Metering - Regional initiatives (e.g., Power Africa, AREI) - Fragmented cross-border governance	- Heavy dependence on foreign direct investment (FDI) and development aid - Frequent use of public-private partnerships (PPPs) - Volatile financing environment due to political and currency risks - Early adoption of green bonds in countries like Nigeria and South Africa

Source: International Renewable Energy Agency (IRENA), 2022, IEA (2023), REN21 (2021), AfDB (2023), UNEP (2021), and European Commission (2020).

While Europe demonstrates the advantages of policy harmonisation and long-term planning, Africa's experience highlights the importance of localised governance innovations and the need for stronger regional policy coordination. Sustainable progress in Africa will depend on building infrastructure and the institutional and financial ecosystems needed to support it over time.

6. Challenges and Opportunities

The trajectory of renewable energy development in Europe and Africa is shaped by structural, institutional, and economic conditions, many of which present significant challenges—but also open vital opportunities for context-specific innovation (Charamba et al., 2025). In Africa, limited grid infrastructure remains one of the most pressing constraints. Many countries still rely on isolated or underdeveloped national grids, making integrating utility-scale renewable energy projects difficult. The lack of transmission capacity is compounded by weak regulatory enforcement, limited local manufacturing, and a shortage of skilled professionals in renewable energy sectors (AfDB, 2023). Financing is also a central barrier: while Africa has seen growing interest from international investors, renewable energy projects are often perceived as high-risk due to political instability, currency fluctuations, and regulatory uncertainty (IFC, 2021; UNEP, 2021).

Nevertheless, Africa's decentralised and flexible market environment has enabled a different kind of innovation. Off-grid and mini-grid solutions are increasingly used to electrify remote communities without waiting for full national grid coverage. Pay-as-you-go solar home systems, particularly in East Africa, are examples of how local innovation—combined with mobile finance and donor support—can address energy access while building renewable capacity (IRENA, 2022). These models offer potential not as alternatives to centralised infrastructure but as parallel systems tailored to rural and underserved populations (Okorie, 2025).

The key challenges in Europe are not access but integration, equity, and political consensus. As renewable penetration increases, grid stability and energy storage have become pressing issues, particularly during seasonal demand shifts and extreme weather events (IEA, 2023). Additionally, the expansion of wind and solar projects has sometimes met local resistance due to environmental or aesthetic concerns, revealing the need for more inclusive energy planning processes. These issues suggest that Europe's renewable transition, while technically advanced, also faces important social and governance questions.

Comparing the two regions reveals not a linear progression but two distinct but complementary pathways. Europe's centralised grid-based model, emphasising regulatory alignment and high-tech solutions, provides valuable insight into systems integration and long-term planning. Africa's experience highlights the importance of modular, affordable, and community-oriented solutions that are responsive to development needs and local realities. The opportunity lies not in replication but in mutual learning and co-development of resilient and adaptive energy strategies.

Conclusions

This study has examined the comparative dynamics of solar and wind energy deployment in Europe and Africa, revealing how geographic, institutional, and economic conditions shape the pathways of renewable energy transition in markedly different ways. While Europe has advanced through a centralised, policy-driven model supported by technological innovation and regulatory coherence, Africa's energy transition is more fragmented but flexible, characterised by decentralised innovations and context-responsive strategies.

The analysis confirms that a one-size-fits-all approach to renewable energy deployment is neither feasible nor desirable. Europe's experience provides insight into grid integration, financing mechanisms, and long-term planning. However, Africa's trajectory—especially in regions like East and North Africa—demonstrates that distributed, low-cost, and adaptive energy systems can offer viable alternatives, particularly in areas underserved by central infrastructure.

The comparison is not about prescribing a universal model but identifying what works, where, and why. It highlights the importance of aligning renewable energy strategies with regional development priorities,

governance capacities, and socio-economic realities. Furthermore, it suggests the value of mutual learning: Africa can draw technical and policy insights from Europe, while Europe can learn from Africa's leadership in decentralised systems and energy access innovation.

Future research should explore these dual transitions through a more granular lens—by country, technology type, or socio-political context—and assess the impact of emerging tools such as artificial intelligence, local energy markets, and regional interconnection. In doing so, scholarship can move beyond comparison toward more constructive models of co-adaptation, where diverse energy transitions are not ranked but coordinated to serve both climate goals and local needs.

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Laila TALBI is a PhD student at the Faculty of Sciences and Techniques of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Renewable energy, Smart Buildings.

ORCID ID: <https://orcid.org/0009-0008-5637-7081>

Mouna ABARKAN is a Full Professor at the Faculty of Sciences and Techniques of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Voltage regulator and Power-on reset.

ORCID ID: <https://orcid.org/0009-0006-8354-6704>

Fatima Ezzahra SABER is a Full Professor at the Faculty of Sciences and Techniques of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Mechatronics.

ORCID ID: <https://orcid.org/0000-0001-8229-6789>

Ahmed LOUARDI is a Full Professor at the Faculty of Sciences and Techniques of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Physics, Materials.

ORCID ID: <https://orcid.org/0000-0002-2822-1468>

Jurga VESTERTĖ is Associate Professor, Department of Business Technologies & Entrepreneurship, Faculty of Business Management, Vilnius Gediminas Technical University. Research interests: Service innovation and modularity, new public service development, decision-support frameworks for service modularisation, and the digitalisation of services—especially within smart service ecosystems.

ORCID ID: <https://orcid.org/0000-0002-4831-1102>

Najiba EL AMRANI EL IDRISSE is Ph.D. professor coordinator of the research team Signals, telecommunications and smart grids at the Faculty of Science and Technology of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Antenna, Antenna Arrays, Electromagnetics, UMTS, Telecommunications.

ORCID ID: <https://orcid.org/0000-0001-5603-1306>

Joana KATINA, Dr. is a Junior Research Fellow in the Department of Business Technologies and Entrepreneurship at the Faculty of Business Management, Vilnius Gediminas Technical University. She also serves as an Assistant Professor in the Department of Computational and Data Modelling at the Institute of Computer Science, Faculty of Mathematics and Informatics, Vilnius University. In addition, she is an Associate Professor in the Software Development Department at the Faculty of Electronics and Informatics, Vilniaus kolegija / University of Applied Sciences. Her research interests include time series analysis, forecasting methods, artificial intelligence, machine learning, and financial markets.

ORCID ID: <https://orcid.org/0000-0002-0715-1675>

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CHALLENGES IN THE REGULATION OF WATER DEMAND PLANNING IN SOUTH AFRICA

Tinashe Mukonavanhu ^{1*}, Danielle Nel-Sanders ²

^{1*,2} Mukonavanhu; College of Business and Economics; School of Public Management, Governance and Public policy; University of Johannesburg, South Africa

E-mails: ^{1*} tmukonavanhu@uj.ac.za (Corresponding author); ² daniellen@uj.ac.za

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Abstract. South Africa is confronted with the challenges of dual governance systems, ineffective implementation of water legislation, and conflicts arising from differing governance approaches, all of which impede the effective management of integrated water resources. This article aims to understand the significant challenges in regulating water demand planning in South Africa. The research methodology employed in this study consists of a rapid review complemented by open-ended interviews, facilitating data triangulation that enables a comparative analysis between insights gathered from interview participants and the results obtained from the rapid review. The rapid review involved a comprehensive examination of fifty-five articles, of which twelve met the established inclusion criteria for the study. Additionally, five managers from the Vhembe district municipality were interviewed. The key dimensions investigated include an evaluation of study quality, a narrative synthesis of study outcomes, an exploration of the barriers and facilitators associated with implementing water demand planning regulations, and interventions designed to support such regulations. The findings underscore significant challenges in regulating water demand planning in South Africa, including project delays, budget overruns, substandard quality of work, mismanagement of funds, and insufficient service delivery. Recommendations emphasize the necessity of implementing water demand forecasting, which serves as a fundamental component of all planning efforts within the water services sector and aims to project the future water requirements of the designated planning area.

Keywords: water demand management; South Africa; water regulation; service delivery; governance

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1. Introduction

The regulation of water demand planning in South Africa (SA) encounters several challenges, including unsustainable water consumption patterns, insufficient infrastructure, accelerated urbanization, corruption, and a deficiency in stakeholder engagement (Adom & Simatele, 2024). SA is currently facing significant challenges related to water scarcity, with an anticipated increase in demand of 17% by the year 2030. Furthermore, it is noteworthy that 37% of urban piped water is lost, underscoring the urgent necessity for effective water management strategies (Feukeu et al., 2022). In 2017, South Africa experienced a notable rise in intermittent water supply, impacting approximately 22 million individuals (Loubser et al., 2021).

The water use license application system in SA is operating ineffectively, which obstructs the achievement of its intended objectives and the fulfilment of relevant constitutional provisions (Moolman et al., 2022). The regulation

of water resources in SA is hindered by issues such as inadequate pricing, suboptimal returns on capital investments, elevated levels of non-revenue water, and a substantial deficit in capital investment (Ruiters & Amadi Echendu, 2022). In SAn urban areas, the average percentage of non-revenue water exceeds 37%, with certain regions experiencing figures as high as 60% (Steyn, 2022a).

The difficulties associated with regulating water demand planning in SA arise from historical disparities, the shift away from riparian rights, and the necessity to integrate social norms to ensure equitable distribution of water resources (Madigele, 2018). SA is characterized by the presence of dual governance systems, inadequate implementation of water legislation, and conflicts arising from differing governance approaches, all of which impede the effective management of integrated water resources (Stuart-Hill et al., 2020). The regulatory framework pertaining to greywater management in informal settlements in SA encounters several obstacles, including inconsistencies, ambiguity, and insufficient enforcement mechanisms (Vala & Malazaa, 2024).

SAn municipalities lack defined responsibilities for collecting essential water service data, resulting in challenges related to the quality, integrity, and timeliness of such data (Steyn, 2022b). In SA, the water infrastructure sector is experiencing significant challenges, including project delays, budget overruns, substandard quality of work, mismanagement of funds, and insufficient service delivery (Aiyetan & Das, 2021). The management of water resources in SA is characterized by inefficiencies stemming from institutional ambiguities, challenges related to policy adherence, and a decline in water quality (Adom & Simatele, 2024).

The present study's authors initiated a participatory research project in collaboration with managers from the VDM between March 2021 and November 2021. The initial phase of the current study involves a systematic search and rapid review of existing academic literature. This will be succeeded by original research, including interviews with VDM managers. Collectively, these two data sources will guide the design and implementation of the study.

2. Method

The study employs a qualitative case study methodology. The case setting is the Vhembe municipality in Limpopo, SA. Data were gathered from participants through open-ended interviews. A non-probability sampling approach was utilized for the interviews, specifically through purposive sampling. This method involves selecting samples based on predetermined criteria pertinent to the research objectives. Purposive sampling, also referred to as purposeful or judgment sampling, operates on the principle that identifying the most relevant cases for the study yields the most valuable data, thereby ensuring that the research findings are directly influenced by the selected cases (Mweshi & Sakyi, 2020).

Purposive sampling was chosen as a methodological approach to identify a specific population and investigate their characteristics, perceptions, and intentions. Deviant case sampling, a subset of purposive sampling, enables researchers to focus on individuals representing the lower or less favourable end of a given scale, thereby facilitating an understanding of their experiences. In this context, the researcher seeks to derive insights from participants perceived as underperforming or experiencing failure (Nyimbili & Nyimbili, 2024). The study employs open-ended interviews with questions designed to elicit detailed responses, promoting a discovery-oriented methodology. In-depth interviews allow the interviewer to maintain an elevated level of concentration and internalization, which aids in establishing rapport and improving the relationship between the participant and the researcher (Roller, 2020).

The interviews were conducted over an extended period, specifically from March 2021 to November 2021, enabling the researcher to gather substantial data. This timeframe facilitated the opportunity to pose follow-up questions and clarify any inconsistencies in the participants' responses. Before the interview sessions,

appointments were arranged in advance with the participants. The researcher engaged in interviews with a total of five individuals, with each session lasting between forty minutes and two hours.

The research methodology employs open-ended interviews in conjunction with a rapid review to enable data triangulation, thereby facilitating a comparative analysis between the insights gathered from interview participants and the results obtained from the rapid review. Rapid reviews have been advocated as an effective approach to delivering timely and resource-efficient literature summaries by utilizing techniques that expedite or optimize conventional systematic review processes (Moons et al., 2021). The objectives of this rapid review encompass the provision of prompt evidence to facilitate decision-making processes and the enhancement of evidence-based decision-making in the regulation of water demand planning within the context of SA (Arevalo-Rodriguez et al., 2023).

This rapid review aims to systematically assess the existing body of knowledge regarding regulating water demand planning in SA. This assessment will facilitate the exploration of the following questions:

- What is understood regarding the regulation of water demand planning in SA?
- What approaches have been implemented by institutions that have effectively managed water demand planning regulations in SA?
- What interventions have been tested and identified as effective or ineffective in enhancing the regulation of water demand planning in SA?

2.1. Search strategy and inclusion criteria for the rapid review

A systematic search of academic journal articles was performed in August 2024, focusing on examining abstracts and keywords within various databases. The databases searched were Scopus, GreenFILE, PAIS Index + Archive, Academic Search Ultimate, Business Source Ultimate, ProQuest Central, and Waters & Oceans Worldwide. Search terms were: “South Africa” AND (regulation OR laws OR statutes OR mandates) AND “(water demand planning” OR “water demand management)” AND (government OR “public management” OR “public sector” OR “public administration)”

The database search yielded a total of 419 items (refer to Figure 1). No further items were sourced from alternative methods, such as ancestry searches of reference lists or tracking the citations of authors. A total of fifty-eight duplicates were eliminated from the dataset. The titles, abstracts, and keywords of the remaining 361 articles were subsequently reviewed to assess their potential eligibility. Fifty-five articles passed the inclusion criteria as they ranked highest based on the mention of the greatest number of words or phrases from the search phrases "South Africa" AND (regulation OR laws OR statutes OR mandates) AND "(water demand planning" OR "water demand management)" AND (government OR "public management" OR "public sector" OR "public administration)" in either their title, abstract, and or keywords. No restrictions were imposed regarding the year of publication to encompass all potentially pertinent articles.

The PRISMA 2020 statement offers a revised guideline for the reporting of systematic reviews and meta-analyses, superseding the 2009 statement. It features a 27-item checklist, an elaborated checklist that specifies reporting recommendations for each item, and updated flow diagrams for both original and revised reviews. The statement aims to enhance the transparency and thoroughness of reporting in systematic reviews, which will be advantageous for authors, editors, and users of these reviews (Matthew et al., 2021).

The terminology associated with systematic reviews and meta-analyses has changed significantly over time. The transition from QUOROM to PRISMA reflects an intention to include both systematic reviews and meta-analyses within its scope. A systematic review is characterized by its focus on a well-defined research question. It employs systematic and transparent methodologies to identify, select, and critically evaluate pertinent studies and gather and analyze data from these studies.

The application of statistical methods, known as meta-analysis, may be utilized to synthesize and summarize the findings of the studies included in the review. However, it is not a mandatory component. Meta-analysis denotes explicitly the application of statistical techniques within a systematic review to amalgamate the results of the studies considered (Ahn & Kang, 2018). The preferred items for reporting systematic reviews and meta-analysis (PRISMA) were used.

A total of fifty-five articles underwent a comprehensive full-text review, identifying twelve articles that satisfied the established inclusion criteria. For an article to be considered for this review, it was necessary to fulfil one of the following conditions: (1) it addressed the regulation of water demand planning in SA; (2) it proposed strategies for institutions to enhance their regulation of water demand planning in SA; or (3) it presented interventions aimed at improving the regulation of water demand planning in SA. Ultimately, only twelve articles were found to meet the inclusion criteria.

2.2. Quality Appraisals

The Strengthening the Reporting of Observational studies in Epidemiology (STROBE) statement and The Joanna Briggs Institute (JBI) are recognized as prominent critical appraisal tools for evaluating the reporting of items in review studies (Borges Migliavaca et al., 2020). Both frameworks exhibited limitations in evaluating the twelve studies under consideration, primarily due to their focus on experimental, quasi-experimental, and systematic research methodologies.

Nevertheless, they contributed to formulating a modified appraisal checklist designed to evaluate the studies' theoretical synthesis and methodological rigour. The quality appraisal checklist consisted of five criteria, each evaluated on a three-point scale: 1 = low, 2 = medium, and 3 = high, resulting in a total score range of 5 to 15.

These criteria pertained to the clarity of the following aspects: definitions of the population; interventions, comparators, or critiques; methodological approaches; considerations of validity, reliability, and theoretical frameworks; and the consistency of results, discussions, and limitations in relation to the stated methodological framework. The overall quality assessment was derived from the mean scores across the five quality appraisal criteria.

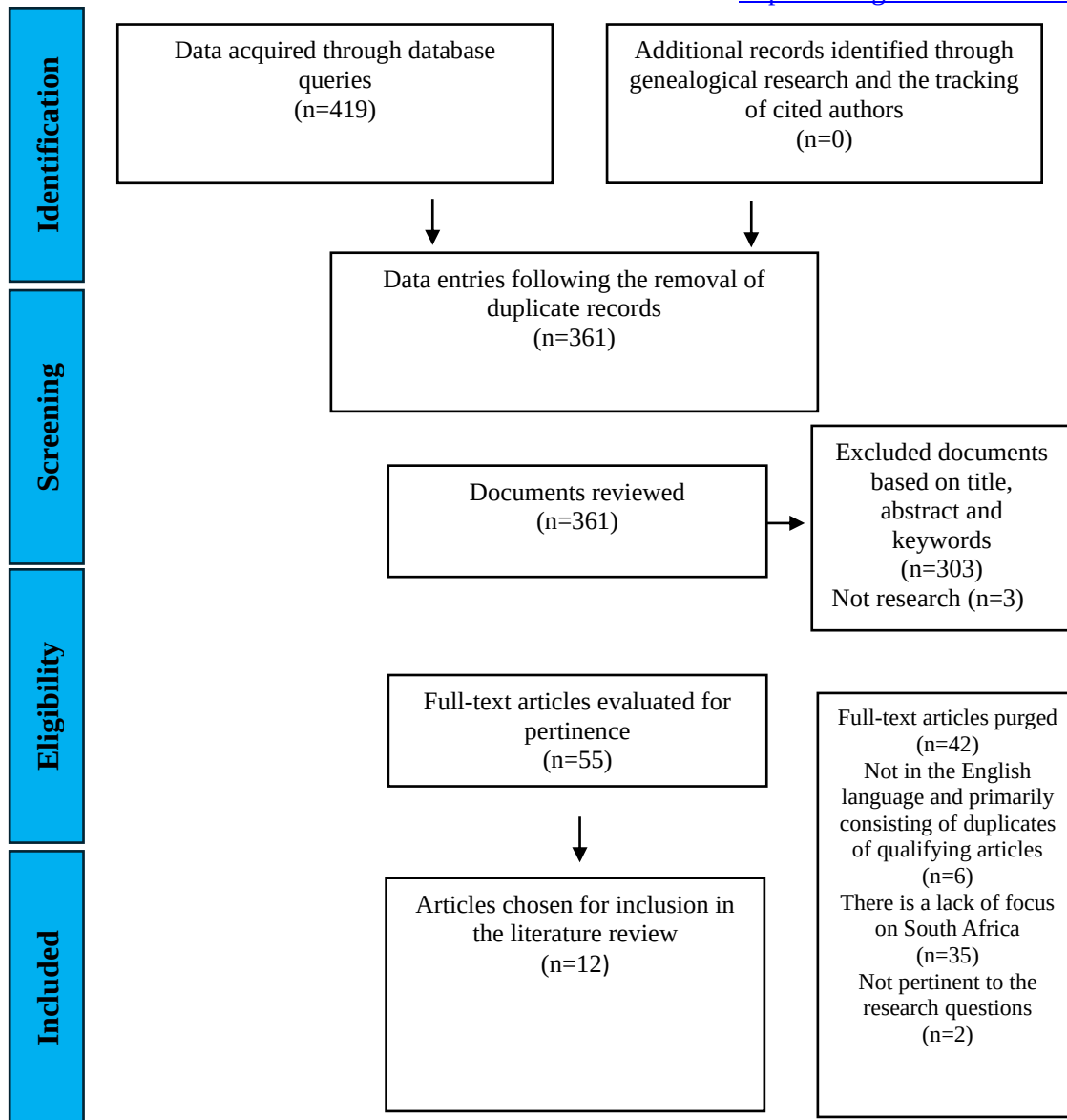


Fig. 1. PRISMA process for reporting rapid reviews

Source: Authors own creation

3. Literature review: results from the rapid review

Data from twelve research studies were systematically extracted and compiled into a summary table (Table 1), delineating the research focus, methodology, and significant findings pertinent to regulating water demand planning in SA. An evaluation of the quality of the studies was conducted (Table 2), which was subsequently followed by a narrative synthesis of the study outcomes. The primary emphasis was placed on identifying the barriers and facilitators associated with implementing regulations for water demand planning, as well as interventions designed to support such regulations. Of the twelve studies evaluated, seven investigated the significance of knowledge pertaining to Water Demand Management (WDM) (Daane, 1998; Mwendera et al., 2003; Colvin & Saayman, 2007; Mathipa & Le Roux, 2009; Wolfe, 2009; Price et al., 2012; Crous et al., 2013; Murwirapachena, 2021).

Wolfe (2009) posits that tacit knowledge is instrumental in influencing WDM practices and their effective execution. Daane (1998) highlights the necessity of comprehending WDM to make well-informed strategic investment choices. Price et al. (2012) point out a significant gap in educational initiatives related to water conservation, advocating for the launch of awareness campaigns to enhance understanding of WDM.

Additionally, Mathipa and Le Roux (2009) reveal that participants in their study demonstrated a deficiency in practical knowledge regarding WDM strategies, thereby emphasizing the critical role of knowledge in promoting effective water conservation practices.

Table 1. Overview of research studies and articles included

Author (Year), Article type	Research Focus	Sample, Research design, analysis	Key findings pertinent to the regulation of water demand planning in SA
(Wolfe, 2009), Academic peer review paper	Examining the implicit knowledge possessed by WDM professionals within municipal contexts	Research Design: A qualitative thematic analysis focusing on the tacit knowledge of WDM practitioners. Sample: Municipal practitioners from Ontario, Canada, and Southern Africa. Analysis: A comparative characterization of both explicit and tacit knowledge related to WDM.	Discussions and practices surrounding WDM are predominantly informed by explicit knowledge. However, the tacit knowledge possessed by practitioners plays a significant role in the implementation and overall success of WDM initiatives.
(Daane, 1998), Dissertation	The implementation of residential water metering in multi-unit high-rise buildings for demand management. The examination of cost recovery strategies within the context of the former Soviet Union (FSU) and Eastern Europe.	The research design encompasses a cost-benefit analysis conducted in Lviv, Ukraine. The sample for this study consists of multi-family residential high-rise buildings in Eastern Europe and the former Soviet Union (FSU) republics.	Utilizing volumetric-based metering in high-rise buildings is an economically efficient strategy for managing demand. Furthermore, the implementation of conservation measures is essential for the effective management of water resources.
(Jiang et al., 2010), Academic peer-review paper	The development of an urban water quota management system in China. Formulation and execution of WDM strategies.	Sample: Urban Water Management Systems in China Research Design: Examination of the effects of water quota management Analysis: Emphasis on water demand, efficiency, and resource distribution.	The management of urban water quotas significantly improves strategies for planning water demand. The implementation of a water quota index system facilitates the effective regulation of water demand. Furthermore, the development of the water quota system has transitioned towards encompassing general industries for enhanced planning purposes
(Jonker, 2012), Dissertation	Water management strategies for electricity generation in SA. Dry cooling systems and wet cooling systems utilization in power plants	Protocols exist that delineate the requirements for water metering in power generation facilities. Conducting an economic analysis of cooling systems is essential in the design of power plants. The primary contributor to Eskom's electricity expenses is the generation function.	Water demand planning is essential for the sustainable generation of power. Strategic action plans have been developed to guarantee sufficient water resources for power generation activities.
(Price et al., 2012), Academic peer-review paper	Water conservation and demand management strategies within the Nelson Mandela Bay Municipality. Strategies for the reduction of water loss and the enhancement of sustainable water service delivery	Research Design: Implementation of Water Loss Management Services in Nelson Mandela Bay. Sample: Water supply zones, water metering systems, and community standpipe facilities. Analysis: Calibration of the network, assessment of pressure measurements, identification of leaks, and analysis of flow dynamics.	Emphasizes the importance of minimizing unbilled authorized consumption and mitigating apparent losses. Effective pressure management is crucial for the sustainability of service delivery.
(Mathipa & Le Roux, 2009), Academic peer- review paper	Training requirements for community-based water management in SA Educational initiatives aimed at promoting WDM and conservation practices in rural communities.	The research design encompassed the collection of data through interviews. The analysis involved the identification of water usage patterns and the development of educational programs. The sample comprised residents from the villages of Mangabane and Makgemeng.	Effective WDM necessitates the implementation of organized educational and training initiatives. Community-oriented programs play a vital role in promoting sustainable water conservation practices. Furthermore, public awareness campaigns are essential for fostering participation in water conservation efforts.

(Crous et al., 2013), Academic peer-review paper	The water demand patterns associated with community ablution facilities in SA. This study examines water consumption associated with laundry activities, toilet flushing, and periods of peak demand. It further analyses water requirements for communal facilities to support hydraulic modelling efforts	The study involved a sample of 233 community ablution blocks (CABs) located within 105 informal settlements, alongside a survey of 1,021 households. The research design incorporated end-use water monitoring, using data loggers, and applying the Weibull distribution to assess peak flow rates. Data analysis was conducted using Microsoft Excel, where missing data was addressed, and peak factors were calculated.	The water consumption for laundry purposes accounts for 60% of total usage, while toilet flushing constitutes 16%. Additionally, the peak demand factors for ablution facilities surpass the established municipal standards. Furthermore, the construction timeline for the CAB project has exceeded the initially allocated budgeted duration, thereby affecting overall project expenditures
(Pienaar et al., 2017), Academic peer-review paper	The implications of water resources associated with the transition to a green economy in the Western Cape Province are examined. A system dynamics model is utilized to assess strategic interventions aimed at facilitating this transition. Additionally, the study identifies various factors that impact both the transition to a green economy and the management of water resources within the province	Research Design: A system dynamics model aimed at facilitating the transition to a green economy. Sample: Stakeholders within the water sector of the Western Cape Province. Analysis: Examination of water demand, costs associated with interventions, and the implications of system dynamics.	The planning of water demand significantly influences the transition towards a green economy in the Western Cape region. The Water Stress Index serves as a tool for assessing risk and directing the implementation of necessary interventions. Additionally, various scenarios have been formulated to effectively manage water demand and promote sustainability.
(Mwendera et al., 2003), Academic peer-review paper	Constraints in WDM within Southern Africa. Approaches to address challenges in the implementation of water sector initiatives	Sample: The study was conducted across six countries and identified various constraints and strategies. Research design: An evaluation of the limitations associated with WDM, along with viable solutions and instances of successful implementation. Analysis: The recommendations emphasize the necessity of adapting to the evolving socio-economic landscape to facilitate the implementation of WDM.	The implementation of WDM is impeded by insufficient resources, which results in a predominant focus on supply-side solutions. It is essential for stakeholders to be informed about the advantages of WDM to facilitate its effective execution. Furthermore, regulatory bodies should designate managers to address issues of non-compliance and to oversee cost recovery processes
(Colvin & Saayman, 2007), Academic peer-review paper	Groundwater governance in Cape Town, SA. The use of the Trialogue model for the management of groundwater. Social, policy, and technological aspects in public sectors	Research design: Interviews, literature review, household surveys. Sample: Public, hydrogeologists, major stakeholders in groundwater governance. Analysis: Evaluating governance mechanisms in Cape Town, alongside the scientific comprehension of groundwater resources	The implementation of WDM strategies resulted in a rise in the utilization of private boreholes. Land ownership reform initiatives have also been designed to promote equitable access to water resources. Furthermore, the level of societal trust in governmental institutions significantly affects patterns of resource utilization
(Ngcobo et al., 2023), Academic peer-review paper	The influence of demographic factors on water consumption patterns in Durban. The implementation of water-efficient technologies within residential settings in Durban	Sample: A cohort of 300 heads of households from various regions within Durban. Research Design: A descriptive methodology employed to examine patterns of water consumption behaviour. Analysis: Utilization of probit regression models to identify factors influencing water-efficient behaviours	Income consistently affects the adoption of water-efficient practices. The level of education plays a significant role in the implementation of water-saving technologies. Additionally, the size of a household serves as a determining factor in the installation of water-efficient technologies.
(Murwirapachen, 2021), Academic peer-review paper	The study examines household water consumption patterns and the adoption of water-efficient appliances in Johannesburg. It also explores the influence of demographic variables on water usage behaviour and the adoption of water-saving appliances.	Sample: A total of 889 households in Johannesburg were surveyed, representing a diverse range of demographic characteristics. Research design: Probit regression models are utilized in the analysis of survey data pertaining to water consumption. Analysis: Descriptive statistics, biographical data, water-efficient appliance adoption patterns	Older, male, and lower-income groups practice efficient water-use behaviour. Biographical variables typically do not significantly impact the adoption of water-efficient appliances. Therefore, it is advisable for policymakers to focus their efforts on younger individuals, women, and households with higher income levels

Source: Authors' creation

Table 2. Evaluations of the quality of the reviewed research

Author (Year, article type)	Clarity of population and/or data set (i)	Clarity of intervention and/or comparator (ii)	Technical rigour and/or theoretical approach (iii)	Validity, reliability and objectivity (iv)	Methodological clarity of results/discussion (v)	Overall study quality (vi)
(Wolfe, 2009), Academic peer review paper	medium	high	medium	high	high	high
(Daane, 1998), Dissertation	medium	high	medium	high	high	high
(Jiang et al., 2010), academic peer-review paper	low	high	medium	high	high	high
(Jonker, 2012), Dissertation	low	high	medium	high	high	high
(Price et al., 2012), journal	low	high	medium	high	high	high
(Mathipa & Le Roux, 2009), academic peer-review paper	medium	high	medium	high	high	high
(Crous et al., 2013), academic peer-review paper	medium	high	medium	high	high	high
(Pienaar et al., 2017), academic peer-review paper	low	high	high	high	high	high
(Mwendera et al., 2003), academic peer-review paper	medium	high	low	high	high	high
(Colvin & Saayman, 2007), academic peer-review paper	high	high	medium	high	high	high
(Ngcobo et al., 2023), academic peer-review paper	high	high	high	high	high	high
(Murwirapachena, 2021), academic peer-review paper	high	high	medium	high	high	high

Source: Authors' creation

3.1. Summary of the Studies Incorporated

The literature review used in this study encompasses twelve research studies that collectively examine water demand planning in SA, reflecting the complex and diverse nature of water management strategies. Wolfe (2009) emphasizes the significance of tacit knowledge among practitioners of WDM. Price et al. (2012) investigate water conservation initiatives within the Nelson Mandela Bay Municipality. Jonker (2012) explores the intersection of water management and power generation, crucial for promoting sustainable water use in industrial settings. Additionally, Pienaar et al. (2017) analyze the ramifications of transitioning to a green economy, while Mwendera et al. (2003) identify the challenges encountered in implementing WDM throughout southern Africa. These studies highlight the critical roles of regulatory frameworks, stakeholder engagement, and effective WDM strategies in achieving sustainable management of water resources in SA.

3.2. Quality of Studies

The research quality across the examined studies was consistent, with all twelve studies classified as high quality. Nevertheless, when considering the specific sub-categories employed to assess the overall quality, certain studies performed less favourably in particular evaluation criteria. For instance, regarding the population and/or data set, Jiang et al. (2010) received a low score due to insufficient clarity concerning the study population, as it predominantly addressed the entirety of China. An additional illustration pertains to the technical rigour and theoretical framework employed in research. For instance, Mwendera et al. (2003) received a low score as the study did not explicitly reference or implement any technical rigour within the research paper.

3.3. The regulation of water demand planning in SA

Numerous studies have engaged in discussions concerning regulating water demand planning in SA. A prevalent theme across these studies is the necessity of integrating technical solutions with institutional frameworks and stakeholder involvement to achieve sustainable water management. The significance of knowledge and expertise in implementing WDM is frequently underscored, as noted by Wolfe (2009), who highlights the impact of tacit knowledge among practitioners on the success of policy initiatives. Similarly, Price et al. (2012) stress the importance of technical interventions, such as pressure management and the reduction of water loss, which are essential for regulatory frameworks to ensure sustainable water services. Both studies assert that effective regulation must incorporate both technical and knowledge-based strategies to yield practical outcomes. Jonker (2012) and Pienaar et al. (2017) converge on the significance of economic and environmental factors within regulatory frameworks, particularly in relation to industrial water usage and transitions towards a green economy. They propose that water demand planning should be aligned with broader economic strategies and environmental policies. Earlier, Mwendera et al. (2003) contend that resource limitations and stakeholder engagement represent significant barriers to effective WDM regulation, reinforcing the notion that regulatory policies must address both technical dimensions and socio-economic and institutional challenges.

3.4. Strategies that have been used by institutions that have made headway in the regulation of water demand planning in SA

Institutions in SA that have effectively regulated water demand planning have utilized a range of strategies that incorporate both technical and participatory methodologies. Price et al. (2012) provide an account of the Nelson Mandela Bay Municipality's successful implementation of water loss reduction initiatives, which included network calibration, leak detection, and pressure management. These interventions contributed to sustainable water service delivery by minimizing unbilled consumption. Jonker (2012) underscores the application of economic analysis in optimizing water management for power generation, focusing on cost-effective cooling systems that align with national water planning objectives. Similarly, Pienaar et al. (2017) examine the employment of system dynamics models in the Western Cape, where strategic interventions to facilitate a transition to a green economy were integrated with effective water demand planning, promoting sustainability through comprehensive resource management. Meanwhile, Mwendera et al. (2003) highlight the importance of raising awareness and building capacity among stakeholders to address challenges in WDM. They assert that effective institutions have prioritized the promotion of understanding regarding the advantages of WDM across various sectors, thereby improving compliance and overall effectiveness.

3.5. Interventions and strategies for improving the regulation of water demand planning in SA

A prevalent theme in the literature concerning interventions and strategies aimed at enhancing the regulation of water demand planning in SA is the integration of technical solutions with community engagement and the strengthening of institutional capacities. Price et al. (2012) concentrate on technical interventions, including pressure management, leak detection, and the reduction of water loss, as means to promote sustainable water services. Wolfe (2009) underscores the significance of incorporating tacit and explicit knowledge among practitioners, positing that training and knowledge-sharing are crucial for improving regulatory practices. Mwendera et al. (2003) highlight the necessity of fostering stakeholder awareness and engagement to address

regulatory and resource-related challenges, advocating for enhanced collaboration between communities and regulatory bodies. Similarly, Pienaar et al. (2017) promote systemic approaches, such as applying dynamic models to forecast water demand within a green economy's framework, ensuring that planning efforts are aligned with broader environmental objectives. These studies indicate that effective regulation is contingent upon a synergistic combination of technical strategies, stakeholder participation, and institutional development.

In the context of a research initiative focused on obtaining insights and recommendations from professionals for the formulation of a WDM Strategic Plan in the Vhembe District Municipality (VDM), participants were posed the question, "Are there supporting statements in the by-laws of the Vhembe District Municipality that facilitate Water Demand Management Strategic Planning?" The researchers utilized Microsoft Excel to systematically organize, manage, tabulate, and graphically represent the individual responses collected from open-ended, semi-structured interviews. Coding of the interview data was done (Table 3). Thematic analysis was employed to explore both semantic and latent themes (Braun & Clarke, 2006). The semantic analysis focused on the explicit or surface meanings of the data, with the researcher refraining from seeking interpretations beyond the direct statements made by participants or the written content. In contrast, the latent approach aimed to identify and examine the underlying ideas, assumptions, conceptualizations, and ideologies that are believed to influence the semantic content of the data (Braun & Clarke, 2006:84).

Table 3. Table of codes from the interview data

Data	Code
By-laws need to be adopted	Poor Implementation
By laws facilitate water demand planning	Regulation
by-laws are subject to periodic review based on prevailing circumstances	Regulation
several by-laws have been established	Regulation
uncertainty regarding whether the provisions of these by-laws explicitly pertain to water demand planning	Poor Implementation; Lack of communication
there are by-laws that address various elements related to water demand planning initiatives	Regulation; Integrated planning
several by-laws have been established to address the issue of illegal water connections	Regulation
the VDM has established by-laws, these regulations are not actively enforced	Enforcement
there is a lack of specific legal provisions addressing particular infractions, such as the use of illegal water connections	Comprehensiveness
the existing by-laws related to WDM within the VDM are sufficient	Regulation

Source: Authors' creation

All interview participants unanimously concurred that the by-laws of the VDM contain provisions that facilitate WDM Strategic Planning. This assertion is corroborated by existing literature, which indicates that water resource management in SA has been hampered by institutional uncertainties, challenges related to policy compliance, and declining water quality, suggesting that there are initiatives aimed at formulating by-laws that support WDM within municipalities like VDM however, these municipalities may be perceived as lacking proactive measures in developing such by-laws due to significant policy challenges, including institutional uncertainties, compliance issues, and the deterioration of water quality (Adom & Simatele, 2024).

One participant in the interview indicated that the by-laws of the VDM facilitate water demand planning; however, the participant expressed uncertainty regarding the current adoption status of these by-laws.

Additionally, the participant noted that the by-laws are subject to periodic review based on prevailing circumstances. This is supported by the literature, with Ruiters and Amadi Echendu (2022) indicating that SA's water regulation is hindered by issues such as under-pricing, suboptimal returns on capital investment, elevated levels of non-revenue water, and a considerable gap in capital investment. These factors suggest a deficiency in funding necessary to facilitate and sustain the expenses associated with the proposal, adoption, and implementation of by-laws pertaining to water demand planning, thereby undermining the efficacy of the processes associated with these regulations.

One interview participant indicated that several by-laws have been established to address the issue of illegal water connections. The participant expressed uncertainty regarding whether the provisions of these by-laws explicitly pertain to water demand planning; however, they noted that there are by-laws that address various elements related to water demand planning initiatives. One participant noted that while the VDM has established by-laws, these regulations are not actively enforced. This participant further indicated a lack of specific legal provisions addressing particular infractions, such as using illegal water connections. Conversely, another participant asserted that the existing by-laws related to WDM within the VDM are sufficient, a claim corroborated by existing literature. The inability to enforce current by-laws pertaining to WDM and the failure to prosecute individuals who violate these regulations can be directly attributed to a deficiency in knowledge regarding WDM. As previously discussed in this study, seven studies from the literature review highlight the significance of WDM knowledge, with some, such as Daane (1998), emphasizing that a comprehensive understanding of WDM is essential for making informed strategic investment decisions. Additionally, Price et al. (2012) underscore the existing gaps in education related to water conservation, while Mathipa and Le Roux (2009) illustrate that participants in their research demonstrated a lack of practical knowledge regarding WDM strategies, thereby highlighting the critical role of knowledge in promoting effective water conservation practices.

4. Discussion of findings

The interview findings conveyed doubts about the existing adoption status of by-laws that facilitate water demand planning within the VDM. It was also revealed via the interview findings that existing by-laws in the VDM do undergo regular reviews in response to changing conditions. This assertion is corroborated by the rapid review data, with Ngcobo et al. (2023) indicating that income levels consistently influence the uptake of water-efficient practices. Additionally, Murwirapachena (2021) emphasizes the challenges related to water demand planning initiatives, noting that biographical factors generally do not significantly affect the adoption of water-efficient appliances. The regulation of water demand planning in SA encounters several challenges, including unsustainable water consumption, insufficient infrastructure, rapid urbanization, corruption, and inadequate stakeholder engagement. SA is currently facing issues related to water scarcity, with an anticipated increase in water demand of 17% by the year 2030. Furthermore, it is noteworthy that 37% of urban piped water is lost, underscoring the urgent necessity for effective water management strategies. In 2017, a significant rise in intermittent water supply affected approximately 22 million individuals in SA, highlighting the pressing demand for water services within the nation.

Tacit knowledge is instrumental in influencing WDM practices and their effective execution. A comprehensive understanding of WDM is essential for making well-informed strategic investment choices. Current educational shortcomings related to water conservation indicate a pressing need for developing awareness campaigns to enhance understanding of WDM. Furthermore, the deficiency of practical knowledge regarding WDM strategies highlights the critical role of knowledge in promoting effective water conservation behaviours. Integrating technical solutions with institutional and stakeholder engagement is essential for attaining sustainable water management. Technical interventions in managing water resources, including pressure management and the reduction of water loss, are necessary to enforce regulatory frameworks that promote sustainable water services. To achieve practical outcomes, effective water demand regulation must incorporate technical and knowledge-

based strategies. Furthermore, economic and environmental factors are significant components of regulatory frameworks, especially in relation to industrial water usage and the transition towards a green economy.

Institutions in SA that have effectively managed water demand planning have utilized a range of strategies that incorporate both technical and participatory methodologies. For instance, the Nelson Mandela Bay Municipality has adopted water loss reduction initiatives, including network calibration, leak detection, and pressure management. These interventions have facilitated sustainable water service delivery by minimizing unbilled consumption. Additionally, the application of system dynamics models in the Western Cape has proven beneficial, as it has connected strategic interventions aimed at transitioning to a green economy with effective water demand planning, thereby promoting sustainability through holistic resource management. The cornerstone of all strategic planning in the water services sector is the forecasting of water demand, which seeks to project the future water requirements of the designated planning area. Forecasting water demand plays a significant role in enhancing early warning systems and improving the assessment of financial service delivery performance by anticipating future growth in water demand. Accurate water demand estimation and forecasting are essential for projecting income, planning infrastructure capacity, and formulating strategies to gradually or rapidly decrease demand in response to drought conditions.

Nonetheless, it is critical to acknowledge the high uncertainty associated with water demand forecasting, particularly over extended timeframes. This uncertainty can be alleviated by implementing anticipatory governance, which enhances the efficiency of the forecasting process. Integrated water resource planning effectively consolidates the uncertainties related to both water demand and supply within a cohesive anticipatory governance framework (Quay, 2015). By embracing the notion of conceptualizing policy as an experimental process, which recognizes the potential for unforeseen results during its execution, the model illustrated in Figure 2 seeks to establish a basis for predicting water balances within the VDM (Quay, 2015). Water balances within the VDM can be projected and assessed, as precisely forecasting water demand and supply is often challenging. These estimates provide insights into the actual conditions on the ground, thereby facilitating improved planning efforts.

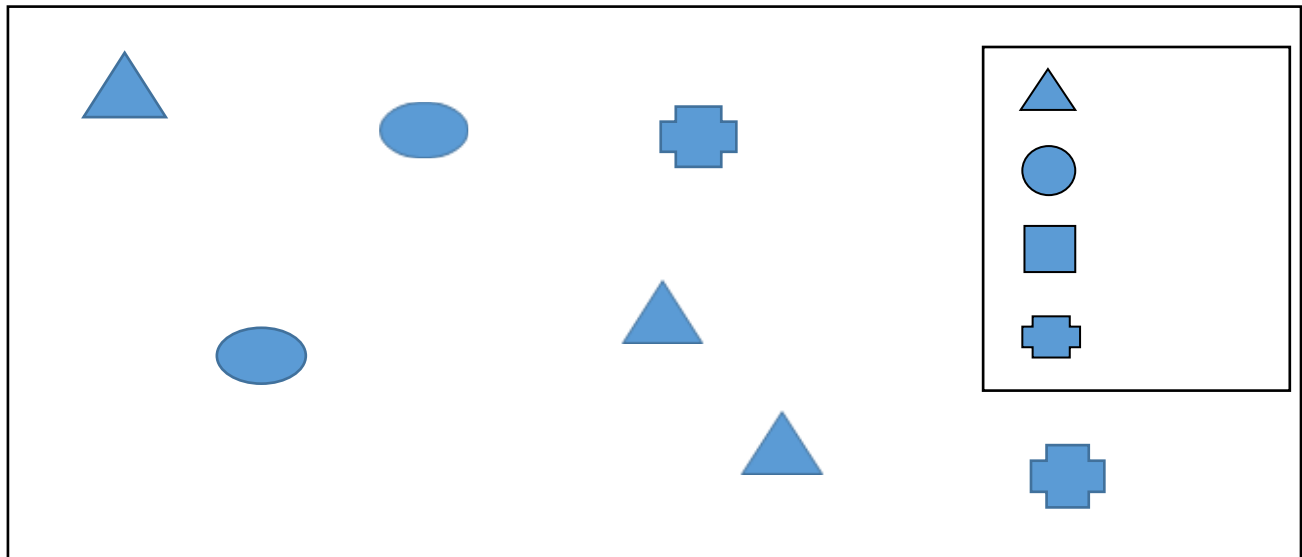


Fig. 2. Water balance forecasting model

Source: Mukonavanhu, 2022

The data obtained from interviews and a literature review on WDM facilitated the creation of a Water Balance Forecasting Model. This model is aligned with the principles of Integrated Water Resource Planning theory.

Utilizing the model depicted in Figure 2, it is possible to generate forecasts for all regions equipped with water meters, thereby estimating their respective water balances. The information collected from these metered regions can subsequently be employed to approximate water balances in areas lacking water meters through techniques such as ratio analysis. As a result, a holistic estimate of the water balance for the entire system can be derived by aggregating estimates from all water usage points. For additional water reservoirs, estimates can be generated using straightforward ratios, such as 1:1, considering size, water capacity, and local demographics. This methodology can be applied to all regional water usage points, encompassing industrial and domestic water consumption. For instance, if one dam provides 300 megalitres of water monthly to a population of 500,000, a comparable estimate can be derived for another dam serving 300,000 individuals by employing a 1:1 ratio to calculate the estimated water usage for the second dam. The following simple formula would be utilized in such scenarios:

$$\frac{300\,000}{500\,000} \times 300$$

Water demand and supply exhibit a natural unpredictability and volatility. Forecasting aims to deliver the most dependable estimates for effective planning. Employing a range of scenarios makes it possible to anticipate various outcomes, facilitating the adjustment of plans to align with real-time conditions as they emerge. As time progresses, the precision of these forecasts is expected to enhance by establishing a thorough framework that leverages online databases encompassing multiple factors affecting WDM. Elements such as population dynamics, climate variations, cultural influences, infrastructure development, and household characteristics, among others, significantly affect water demand and supply.

To effectively regulate water demand, there is a need to comprehend how much water is present in the drainage basin presently as well as how much water will be available in the near future as well as in the distant future. This will help regulators to adopt and formulate flexible and responsive plans that align with current and future water demand patterns. For example, the knowledge that there will be higher water demand in the coming season or years will help regulators to formulate policy that helps to reduce water loss or water use, such as increasing tariff rates or introducing stricter penalties for criminals caught illegally connecting to water sources.

The Water Balance Forecasting Model is designed to enhance the forecasting of water demand, a critical component of any water management strategy. This model assesses the volume of water needed in a designated area over various timeframes, including days, months, or years. The forecasting methodology employed can be linked to the Integrated Development Plan (IDP) and its alignment with Medium Term Expenditure Frameworks (MTEF). The MTEF emphasizes budgeting over three years to optimize financial management (Musoma et al., 2016). The elements included in the Water Balance Forecasting Model are detailed in the following sections:

Reservoir: The proposed Water Balance Forecasting Model aims to enhance the estimation of water volumes in reservoirs lacking metering systems, thereby addressing the challenges faced by the VDM regarding unmetered reservoirs and water tankers. Furthermore, this model will enable the VDM to refine its assessments of water consumption. A considerable amount of water distributed to communities within the VDM remains unrecorded, largely due to complications associated with metering and billing processes. In certain areas of the VDM, there are no records of the water extracted, and metering is only conducted at the command reservoir (Vhembe District Municipality, 2024).

Sanitation Plant: The apartheid era resulted in disparities in sanitation services between rural and urban regions. The Water Balance Forecasting Model can assist the VDM in monitoring the development and expansion of sanitation facilities (Brauns & Stanton, 2016). This will assist the VDM in tracking advancements in sanitation service provision per the IDP's objectives of diminishing the water access disparities resulting from

discriminatory apartheid policies (Cole et al., 2018). This further aligns with one of the main goals of the WDM, which emphasizes the importance of water conservation and the promotion of social development (Isbell, 2020).

Household: The suggested Water Balance Forecasting Model can enhance the VDM's ability to estimate Non-Revenue Water (NRW) more precisely by utilizing data from metered households to infer water consumption in unmetered ones. This methodology can further aid in developing policies designed to lower overall water usage among households. Moreover, the model may facilitate more effective water distribution, which could reduce water waste and increase supply for households lacking piped water. Enhanced estimations of household water consumption can also play a crucial role in establishing equitable and accurate water tariffs, thus decreasing NRW (Vidal-Lamolla et al., 2024).

Industry: The suggested Water Balance Forecasting model promises to improve accountability in the industrial sector by enabling more precise assessments of water consumption in industries. Such advancements could result in greater efficiency in the utilization of water resources, thereby encouraging innovation and promoting water conservation. This, in turn, may stimulate economic growth through enhanced operational efficiency and innovative practices, aligning with the objectives of fostering efficiency and effectiveness in the public sector. Additionally, the model's dependence on online databases for collecting and distributing data related to industrial water usage can significantly improve communication and information sharing.

Conclusions

Improving water resource management necessitates adopting water demand planning, which facilitates sustainable utilization of water resources. As an essential management function, planning is integral to the fundamental operations of any organization. It enables organizations to manoeuvre through intricate and competitive landscapes effectively. During periods of difficulty, strategic planning becomes paramount in guiding decision-making processes. The benefits of planning are numerous, encompassing the establishment of the organization's strategic direction, the alignment of activities with objectives and outcomes, the enhancement of collaborative efforts, the anticipation of both expected and unexpected challenges, the promotion of adaptability to change, and the provision of a robust foundation for informed decision-making.

This research offers a thorough analysis of the challenges that impede effective regulation of water demand planning in South Africa, specifically focusing on the Vhembe District Municipality. The results indicate that, although supportive by-laws and strategic frameworks are in place, the implementation is lacking due to institutional uncertainties, insufficient enforcement, limited engagement from stakeholders, and considerable knowledge deficiencies among practitioners. The originality of this study is found in its combination of a swift literature review with qualitative insights gathered from municipal managers, providing a triangulated viewpoint that connects theoretical knowledge with practical situations. Additionally, the creation of the Water Balance Forecasting Model signifies a notable practical advancement. This model improves the precision of water demand forecasts in metered and unmetered regions and facilitates anticipatory governance and integrated planning. Its utilization can enhance financial planning, infrastructure development, and fair water distribution, especially in municipalities facing resource constraints. By aligning water demand forecasting with broader developmental frameworks such as the Integrated Development Plan (IDP) and the Medium-Term Expenditure Framework (MTEF), this study offers a replicable resource for municipalities throughout South Africa to fortify their water governance systems and encourage sustainable management of water resources.

Implications, limitations and recommendations

The research findings present several implications for policy-making and decision-making in local government. Forecasting water demand in local government is essential for strategically planning water services. The Water Balance Forecasting Model developed in this research provides inputs to policy-making to integrate WDM into local government and to aid decision-making and strategic planning in local government.

A limitation of the study is that it focuses on a single case study. However, this is sufficient as this research is qualitative and does not seek to generalize and replicate findings but to understand and interpret a specific reality within a particular context, such as in the Vhembe District Municipality. However, future research on different case studies comparing rural versus metropolitan municipalities will provide useful evidence-based data for policy-making.

WDM significantly improves coordination, strategic development, and financial performance in municipal water services, and therefore, it should be vigorously promoted within the framework of the VDM. It is essential to strengthen the coordination and alignment of WDM initiatives to enhance transparency, accountability, and the sharing of knowledge and skills. Furthermore, the VDM should support a unified, comprehensive development plan that incorporates all pertinent strategies, including WDM, while ensuring that the municipality's current resources and capabilities effectively align with the implementation process.

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Tinashe MUKONAVANHU has a PhD in Public Management, Governance and Public Policy. Dr Tinashe Mukonavanhu is a Postdoctoral Research Fellow at the University of Johannesburg. Research interests: multi-disciplinary studies, 4iR, WDM, water demand planning, smart governance, electronic governance, public private partnerships, development studies

ORCID ID: <https://orcid.org/0000-0002-5933-9469>

Danielle NEL-SANDERS is a full Professor at the University of Johannesburg and obtained her Doctorate from the University of Johannesburg in Public Management and Governance. Research interests: political risk analysis, risk management, alternative service delivery, public private partnerships and sustainability management

ORCID ID: <https://orcid.org/0000-0001-9896-3566>

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INEFFECTIVENESS IN AFRICAN POLICY RESPONSES TO THE COVID-19 PANDEMIC

Hardlife Zvoushe

University of Johannesburg, School of Public Management, Governance and Public Policy, Johannesburg, South Africa

E-mail: hzyvoushe@sociol.uz.ac.zw

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Abstract. While the research output on policy responses in many African countries has sufficiently captured numerous country cases, experiences, and challenges encountered, almost all of it falls short in explicating the role of policy design challenges in packaging social policy responses to the COVID-19 pandemic. This paper deploys the policy design lenses to explain the ineffectiveness of Africa's policy responses to the pandemic. Built from a scoping literature review, the paper's point of departure is the realisation that policy responses to the pandemic constituted 'policy-making in a crisis context', which explains policy design missteps committed in the typically fire-fighting mode prompted by the emergency. Observed key design blunders in the formulation of responses include flouting the diversity, equity, and inclusivity (DEI) principles, limited compatibility of the selected policy instruments, and, most importantly, misjudgment of the context-capability/ capacity trade-offs in addressing the pandemic-induced social vulnerabilities. The paper's conclusion makes a case for increasing attention to the policy design phase of policy-making as a critical prerequisite for successful policy action in a crisis of the magnitude of a pandemic.

Keywords: African responses; COVID-19; design; ineffectiveness

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1. Introduction

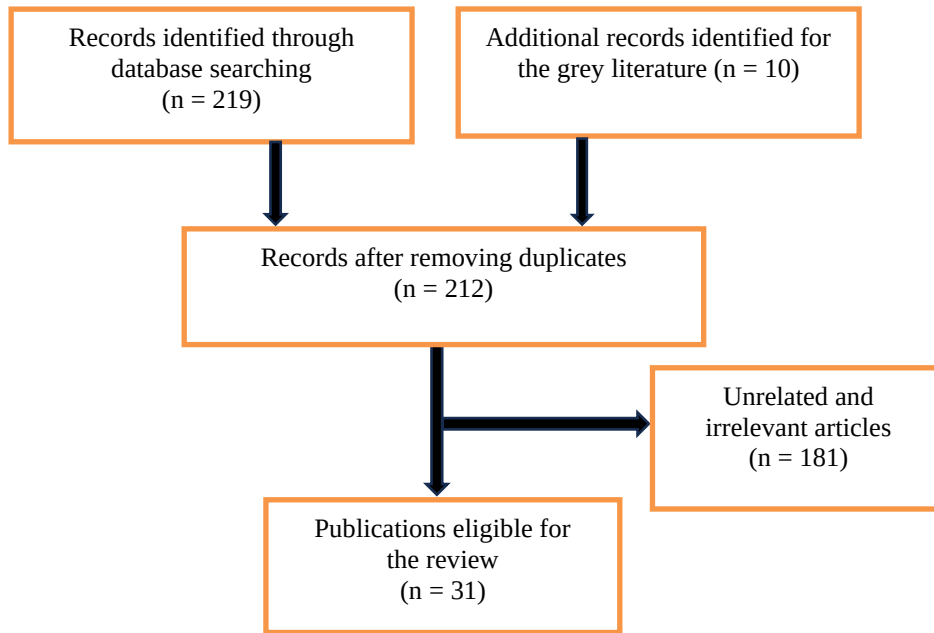
At a global level, literature teems with the condemnation of governments supposedly for their underwhelming responses to the COVID-19 pandemic (Brown, 2021). Disapprovals of governments' levels of preparedness to contain and manage the global health emergency equally abound (O'Dowd, 2021). Observers judged the responses as reflective of governmental failure in managing the global health crisis, some attributing this failure to the interface dysfunction between institutions producing expert scientific knowledge and key decision-makers in government who formulate policy (Colglazier, 2020). However, these sentiments and the related hard feelings against governments overlooked the fact that the COVID-19 pandemic, as a rare global macro-event, introduced multifaceted, cross-sectoral, and overlapping challenges that constrained efficacious policy responses by governments (Bergant & Forbes, 2023). Africa recorded its first COVID-19 case on 14 February 2020 in Egypt, which spread to 52 countries by the end of April. Notably, the pandemic arrived in an already vulnerable environment, plagued by economic factors not directly connected to the global health crisis, such as declining global demand (Paci, 2021). World Bank surveys of 2020 indicated that the COVID-19 pandemic substantially negatively impacted livelihoods and employment, especially for the already vulnerable populations such as the informally employed, unemployed, and the poor (Paci, 2021). One aspect measured by the surveys was job losses

during COVID-19 as a percentage of the employed population before the pandemic. On this factor, Kenya and Gabon had the highest scores, 62% and 61% respectively (Paci, 2021). These two were followed by the Democratic Republic of Congo (DRC) with 42%, South Sudan (39%), Central African Republic (33%), then Ghana and Mali with 29% apiece (Paci, 2021). Further, in a sample of eight (8) countries (Gabon, South Sudan, Ethiopia, Malawi, Uganda, Zambia, Mali, and Madagascar), the average income loss in the COVID-19 period was 70.7% (Paci, 2021). Food insecurity has been another primary concern since the beginning of the COVID-19 pandemic. In East Africa alone, the UN-Habitat (2020) estimated that the number of food insecure will increase beyond 41 million in 2020.

There were widespread concerns about the socioeconomic consequences of actions to contain the global health emergency (UN-Habitat, 2020; Dzawanda et al., 2022; Khowa et al., 2022). The central argument advanced by this paper is that while a lot has been published about governmental responses to the novel coronavirus, there is not much literature evaluating the effectiveness of policy designs in containing the pandemic while minimising the impact of governmental policy actions on livelihoods and the broader social aspect of the populations. The paper argues that lapses and challenges faced in governmental efforts to combat COVID-19 mostly emanated from design-related weaknesses more than anything else. The African design environment/ spaces were not quite conducive for effective policy responses to the health crisis despite the region's delayed spread of the pandemic. The paper adopts the policy design in/effectiveness concept as an analytical framework for dissecting the design issues arising from responses to the COVID-19 pandemic in Africa. It is organised as follows: it first unpacks the responses of African governments to the pandemic, outlining both the hard and soft approaches governments adopt. This is followed by a presentation of the concept of policy design (in)effectiveness, which serves as the analytical framework for appreciating the role of policy design in the failures, limited effects, and challenges associated with governmental responses to the COVID-19 pandemic in the African region. The section that follows presents a discussion of the specific design issues arising from the design environment, with far-reaching implications for the effectiveness of chosen policy actions to contain the pandemic. Lastly, the paper analyses some of the key design missteps of African governments.

2. Methodology

This review paper is predominantly qualitative and is guided by the interpretive research philosophy. Document searches were conducted on databases such as Google Scholar, EBSCO, Research Gate, and Web of Science. The study focused on papers on governmental responses to COVID-19 in the African context. Still, although generic studies about the African region were considered, priority was given to specific country cases on responses to COVID-19, including country experiences (challenges, successes, and weaknesses). Search terms included "COVID-19", "pandemic", "African response(s)", "health policy", and "health crisis responses". The inclusion criteria included documents focused on country responses to the COVID-19 pandemic, and papers focused on challenges experienced in responding to the pandemic. The exclusion criteria included papers that focused on COVID-19 responses outside the African continent and technical, medical papers that focused on lab-based experimental aspects. The database search that was conducted on 07 February 2025 yielded a total of 219 publications, and additional documents identified from grey literature were 10. Duplicate papers removed were 17, and unrelated papers rejected based on the stipulated inclusion/ exclusion criteria were 128. Papers that were eventually included in the final analysis were 31. However, to draw insights for analytical purposes, the paper also included literature on policy design effectiveness, ineffectiveness, and policy failure, which totalled 17. Figure 1 summarises the steps followed in document selection.

**Figure 1.** Systematic scoping review diagram*Source:* Author

3. African governments' responses to COVID-19

WHO declared the coronavirus disease as a public health emergency of international concern (PHEIC), and following the recommendations of the International Health Regulations Emergency Committee, countries of the world were required to make the necessary preparations for the containment of the disease. Much of the government's response actions were drawn from the WHO's guidelines for the prevention, surveillance, and management of the COVID-19 pandemic (WHO, 2020). Further, the Africa Centre for Disease Control (CDC) also prepared COVID-19 guidelines for African Union member states. Among these were non-pharmaceutical interventions such as mobility restrictions, social distancing, limiting mass gatherings, hand hygiene, border controls, and mask use. Different countries conducted active surveillance of COVID-19 cases and potential cases. Countries including Algeria, Angola, Kenya, Mauritius, Nigeria, and Uganda implemented case notifications and virological, mortality, and hospital-based surveillance. However, this was done at varying levels of implementation (Adebisi, Rabe & Lucero-Prisno, 2021).

Surveillance was closely related to contact tracing, which involved identifying, assessing, and managing people who have been in contact with or exposed to an infected person. Persons with COVID-19-like symptoms and confirmed COVID-19 cases with mild symptoms were isolated/ quarantined and monitored closely. Other actions included lockdowns, curfews, closure of schools, and bans and limits of mass gatherings. Following the WHO guidelines, lockdowns could only be lifted once a health system could test, trace, quarantine, and treat COVID-19 cases (Makombe, 2021). Governments further implemented social protection mechanisms as coping strategies to assist the poor and vulnerable populations and provide social insurance to those unemployed with the break-out of the pandemic. Many African countries created varied cash transfer schemes to mitigate the effects of the pandemic on communities and businesses.

In many cases, finer categories of beneficiaries were created: poor families, female-headed households, older persons, and low-income informal groups (Devereux, 2021). Social solidarity funds were established in countries of North, West, Central, and Southern Africa. These initiatives were funded through seed money from governments and contributions from private sector players to support informal traders, small to medium-sized enterprises, and larger corporations facing viability challenges during the pandemic (Devereux, 2021). Cases such as Togo created cash transfer schemes specifically to assist informal workers affected by the pandemic. South Africa disbursed funds to vulnerable households through an unemployment insurance fund (UIF) and a social relief of distress grant. However, experiences with these schemes show a high incidence of non-collection, corruption in the disbursement of financial assistance, and failure of employers to remit received funds to beneficiaries (Khowa et al., 2022). Table 1 summarises the policy tools that African governments adopted in responding to the COVID-19 pandemic. As discussed later, this paper argues that the extent of success with these tools was constrained by design-related issues, such as tool incompatibility, where governments adopted tool mixes or combinations, and the inhibitive contextual variables in the policy environment.

Table 1. Policy tools adopted by African governments in responding to COVID-19

Information tools	Authority tools	Expenditure tools	Organisation tools
Awareness campaigns and health promotion	Mobility restrictions and border controls	Economic stimulus packages for companies	Creation of national testing centres
Notifications and moral suasion	Social distancing and mandatory masking	Cash transfer schemes and social cushioning	Surveillance, investigation, case notifications and case management
Sharing periodic reports, updates, and briefs	Mandatory testing	Relaxed terms of taxation for businesses	Contact tracing, quarantining and treatment
Data collection	Lockdowns and curfews	Development partners' financial support	National laboratories and hospitals
	Banning of social gatherings	COVID-19 national funds	Prevention and control of infections
	Closure of schools, businesses		Vaccination

Source: Author

4. Policy design (in)effectiveness

In simple terms, policy design involves conscious efforts by governments to respond to public problems emerging in specific contexts (Howlett, 2019; Howlett & Mukherjee, 2017; Olejniczak, Śliwowski & Leeuw, 2020; Linder & Peters, 1984). In doing so, governments have an array of policy tools from which they prepare combinations or mixes of tools to achieve specific goals related to the problem(s) to be addressed. While the motivation for selecting and deploying policy tools is presumably the pursuit of effectiveness in achieving desired goals, the selection of policy tools is not a straightforward case. Capano and Lippi (2016) explain that the context within which instrument selection takes place is complex, frequently characterised by "uncertainty, technical complexity, political salience, conflicting values, interests, preferences, coalitions and legacies" (p.6). Given this, decisions on tool selection are significantly influenced by a combination of contextual factors in a given situation. The central goal of policy design is achieving effectiveness (van Geet, Verweij, Busscher & Arts, 2021), which is realised when a good fit is established between the selected instrument(s) and set targets, ultimately resulting in the formulation of policies that deliver desired outcomes. Mukherjee, Coban & Bali (2021) explained that effectiveness in policy design occurs at three nested levels: first, at the design space/ systemic level, where the requirement is to create a conducive environment for effective policy design. At this level, policy design is influenced by the broader sectoral policy styles, traditions, and the obtaining political conditions. In the case of the COVID-19 pandemic, responses would be conditioned by past responses to health crises and emergencies. Hence, the conditionalities presented by the attendant factors in the design environment can promote or inhibit effective policy design. Designers' creativity and choices are shaped by current political conditions, available public capacities, legacies and traditions that often help preserve long-running path dependencies in specific sectors. A study by Bali, He and Ramesh (2022) confirmed this with the observation that the window opened by

the COVID-19 pandemic for health sector reforms was not big enough to cause a break with the "entrenched path dependencies and structural interests" (p.1) in the health sector. Second, effectiveness at the level of instrument mixes, which involves generating fitting combinations between tools and goals. It further entails ensuring coherence, consistency, congruence, and goodness of fit (Bali, Capano & Ramesh, 2019) between the clusters of policy tools addressing different elements of the same policy (Mukherjee, Coban & Bali, 2021). The guiding question becomes: 'How effective are the policy instrument mixes in realising expected goals and outcomes?' Third, effectiveness at the level of individual instruments concerns the efficacy and calibration of individual policy tools to achieve specific policy goals (Mukherjee, Coban & Bali, 2021).

5. Critical issues in the African design environment/space

5.1 Crisis in the economic systems

The COVID-19 pandemic-induced state of emergency gave governments few to no options for optimal manoeuvring in balancing responses to the health crisis and permitting regular on-site business and industrial operations. The observable net picture indicates an increased financial burden and plummeting revenue flows. Drastic response actions such as lengthy lockdowns and border closures became common. They led to cuts in international trade, rapidly shrinking fiscal space, closure of organisations, and suspension of on-site business operations (Khowa et al., 2022). Only organisations with operations amenable to teleworking and virtual operations could sustain business under restricted human movements. This resulted in significant job losses, salary cuts, and, ultimately, a drop in tax-based revenues to governments. 2020 for example, the IMF estimated Zimbabwe's real GDP to contract by 7.4% (IMF, n.d.). With these developments came a drop in the financial capacities of governments to fund response actions such as social protection schemes to help vulnerable populations cope with the pandemic. Thus, cash transfer schemes had limited effectiveness in different countries. The financial situation was further compounded by long-running cases of public debt and inflation, which had their toll on governmental responses to the global pandemic (Adeniran, 2020). By 2018, a year before COVID-19 broke out, Africa's average central government debt as a percentage of GDP stood at 61.4% (Chandler, 2020). By 2022, Africa's combined debt stood at US\$1.8 trillion. This level of debt limited the potential fiscal and monetary stimulus that governments could proffer under conditions of limited production and plummeting revenues (Bergant & Forbes, 2023). The combined effect of the drop in international prices and the arrival of the COVID-19 pandemic drove African countries into borrowing. Following the drop in oil prices, Nigeria had to borrow US\$3.4 billion from the IMF. Egypt, having already borrowed US\$2 billion from the IMF, sought US\$5 billion in loans to compensate for the budget shortfalls caused by the pandemic (Chandler, 2020). But even before the coming of the pandemic, many countries in the African region were already servicing debts, sometimes making fiscal allocations that were bigger than some critical service areas such as healthcare. The complicated debt situation in Africa led some to propose suspending or cancelling Africa's debt to allow the region some fiscal space for financing COVID-19 response actions (Mahamat, 2020). Africa needed an estimated US\$200 billion to finance COVID-19 response actions (Mahamat, 2020) sufficiently.

5.2 Preparedness to contain COVID-19

One important aspect that impacted the effectiveness of the design of African governmental responses to the novel coronavirus was the level of preparedness for the health emergency. When the pandemic started, the African region had only two referral laboratories equipped with the reagents needed for conducting coronavirus tests (WHO, 2020). Hence, from the early stages of the spread of the pandemic to the continent, countries' preparedness was still very low, with no capacity available for the diagnosis and detection of cases. In January 2020, WHO (2020) singled out 13 African countries at a higher risk of exposure to the pandemic because of their direct links or significant travel volumes in and out of China. When the pandemic started, interventions such as social protection mechanisms in much of the Global South were viewed as 'patchy and dysfunctional' (Leisering, 2021). Social protection policies could not adequately address the upsurge of poverty from increased unemployment, welfare losses, and inequalities triggered by the pandemic.

5.3 The pandemic and complexity

For some, the COVID-19 pandemic easily passed for the metaphorical Black Swan because of its extreme rarity, outlier status, and pronounced deviation from outbreaks familiar to the world. Starting as an epidemic in Wuhan, Hubei Province in China in December 2019, its dramatic spread across regions of the world pushed it into the proportions of a pandemic by 2020, and in the process, overstressing even the strongest of national health systems (McConnell & Stark, 2021). The complexity of the pandemic lay in its huge, unprecedented, cross-cutting impact on different sectoral systems: “it generated unexpected crises in the national health systems, economic systems, educational systems, cultural systems, sports systems, and social systems” (Bratianu, 2020:411). More importantly, correlations and tight coupling were observed between these systems, that is, between the crisis in the health system and the economic system, between the sociocultural system and the health system and the economic system, etc. (Bratianu, 2020). Complexity literature shows us that where systems are tightly coupled, the chances that “a crisis will cascade into further systems” are high (Walby, 2022:505). Therefore, The complexity aspect brought with it turbulence and disruption, leading to complications in terms of the design of possible government policy response actions. Complexity was further introduced by the co-occurrence of three categories of challenges: first, biomedical challenges, including unavailable or limited testing capacity, shortage of medical supplies and infrastructure, and limited specialised research capacity (Umvilighozo et al., 2020); second, sociocultural challenges such as infodemic, misinformation, cultural barriers, and limited appreciation of the required health habits during the crisis; and third, economic challenges such as the drop in international trade, fall in revenue, and job losses, among others. It is the cross-cutting nature of the COVID-19 impact that called for policy integration in governmental responses, that is, “the combination of policy goals and policy instruments from different policy sectors into a single policy programme” (Maggetti & Trein, 2022:54). But for such integration to work best, it required the designing of a “complex multi-level policy mix” that ensured a coherent response (Maggetti & Trein, 2022). At this point, African public administrations fell short in capacity to successfully integrate multi-sectoral policy goals and policy instruments, for instance, ensuring coherence between goals of cushioning the vulnerable, goals of public health, and goals of economic growth/sustainability. In another perspective, the complexity of COVID-19 alternatively emanated from the diversity of factors driving the pandemic (age, gender, disabilities, climate, socio-economic status, geographical location, handwashing practices, and mobility trends), which often played out against differences in demographics, trends in human mobility and capacities of health systems (Reid, 2021). Complexity and turbulence call for public sectors to become robust in “adapting and innovating policies, programmes, and services” (Carstensen, Sørensen & Torfing, 2023:36). However, considering the “anti-innovation DNA” that some scholars (see Carstensen & Bason, 2012) observed in the public sectors generally, this proposal would not fly.

5.4 (Un)availability of institutional infrastructure

When the COVID-19 disease broke out, and the manner it heavily impacted the health systems of developed countries in the West and Asia, worse consequences were expected in Africa on account of its poor health infrastructure and general fragility of the health systems (Gilbert et al., 2020). In times of health crises, the success of response actions of governments partly depends on the availability of requisite institutional infrastructure in a country (An & Tang, 2020). In line with institutional arrangements for responding to crises, Yan et al. (2020) explained that such arrangements can be formal (involving government machinery for policy-making and implementation) or informal (involving the public, non-governmental organisations, and other societal actors outside government). For several Sub-Saharan African countries, the history of past outbreaks such as Ebola meant the existence of a certain level of institutional arrangements for responding to and managing the pandemic. Dzinamarira, Dzobo & Chitungo (2020) counted on the possibility of leveraging existing health infrastructure and systems established for countries hit by the Ebola Virus Disease (EVD) between 2013 and 2016. Differences in responses to COVID-19 further depended on whether the existing institutional regimes were centralised or decentralised. Centralised systems typically favoured top-down implementation of policy responses to COVID-19, while decentralised systems distributed responsibilities across the tiers of the governance system.

5.5 Authoritarian heavy-handedness

While some have lauded the proven connection between authoritarianism and efficient pandemic management (Ha, Knox & Janenova, 2024), the scenario was not the same with African authoritarian regimes (Eboko, 2021). The pandemic afforded African authoritarian governments a window of opportunity for the consolidation of power by deploying instruments of repression under the guise of instituting measures to contain the spread of the pandemic. Restrictive measures supposedly to support public health concerns were often ruthlessly applied and could perfectly serve to silence dissent and quell political protests from restive populations. In North Africa, the authoritarian regimes of Algeria, Egypt, and Morocco used the COVID-19 health crisis as a springboard to exploit emergency powers to consolidate their grip on power (Badran & Turnbull, 2022). In Southern Africa, Kamuti (2020) observed the abuse of human rights by the Zimbabwean government, which had already been constantly managing a volatile political situation fuelled by a deep economic crisis. The government found convenience in deploying internationally approved tools such as lockdowns and further declare a state of emergency, which helped severely curtail human traffic in and out of towns and in public places. The government's heavy-handedness in applying containment strategies around the pandemic raised questions regarding the real motive behind the government's execution in the circumstances (Kamuti, 2020). It smacked of the government's well-known authoritarian tendencies in muzzling anti-state voices in the country. In those circumstances, Chenzi and Ndamba (2023) explain that the government's heavy-handedness in the execution of lockdowns, curfew hours, and other restrictive instruments largely affected a large number of informal groups in the country whose livelihoods and survival were abruptly cut by the restrictions on movement.

6. Design missteps

6.1 Sidestepping DEI principles

Governmental policy responses to COVID-19 had implications for handling diversity, equity, and inclusion (DEI) principles among the African populations equally affected by the global health emergency. What varied in the effect of the pandemic among the people was how much they were affected and the differences in how it impacted them. Hence, while some were relatively privileged to have continued access to means of livelihood, the vulnerable and marginalised populations were on the receiving end. Lockdowns, curfews, and other restrictive measures affected livelihoods differently, implying a disproportionate impact on the poor (Chiukira, 2022). There were systemic inequities in many countries. These exposed the age-old structural barriers to the realisation of equity. In a number of African countries, while it is ideal to incorporate DEI principles in national policies and policy-making, not much has been done in most countries, leaving the long-standing postcolonial social and structural barriers unaddressed. Experiences from social sectors such as education and health may be cited for demonstrative purposes. In the education sector, for example, school closures exposed inequities and inequalities in different African countries. While learning continued virtually in many cases, this route seemed to ignore that at least 89% of learners in Sub-Saharan Africa had no access to computers at home, with a further 82% lacking access to the internet (Moyo-Nyede & Ndoma, 2020). Surveys conducted by the World Bank revealed low participation in e-learning by children in many Sub-Saharan African countries. For example, in Mali and Malawi, only three (3) in 10 and less than two (2) in 10, respectively, were participating in online learning (Paci, 2021). But despite these realities, UNESCO was collaborating with African governments in launching programmes to capacitate teachers in managing distance and online learning (UNESCO, 2021). Inequities further arose from the economic stimulus packages by governments, which were not sensitive to the structural marginalisation of vulnerable groups in society, especially those outside the formal economy. When the Government of Zimbabwe released the ZWL\$18 billion Economic Recovery and Stimulus Package in May 2020, for example, only formalised small and medium enterprises (SMEs) benefited, and other equally deserving groups in the informal sector were excluded (Chiukira, 2022). In the health sector, the exposure of medical frontline personnel to the pandemic was pronounced in cases where personal protective equipment (PPE) and mechanical ventilators were in short supply. The shortage of PPE negatively impacted the government's responses to the pandemic. In the case of Zimbabwe, at least 1500 doctors across the country were reported to be working without adequate PPE, raising

their risk of contracting the disease (Mavhinga, 2020). This eventually led the doctors and nurses to strike and sue the government for the lack of PPE in public hospitals (Mavhinga, 2020).

6.2 Underestimating context-capability/capacity trade-offs

Policy studies emphasise the importance of capacity in realising effective policy design and, subsequently, expected policy outcomes (Wu, Howlett & Ramesh, 2015; Mukherjee, Coban & Bali, 2021). Capacity needs in the COVID-19 situation came in multiple dimensions: coordination capacity, analytical capacity, regulatory capacity, and delivery capacity (Lund-Tønnesen & Christensen, 2023). Several African health systems were grossly under-equipped to respond to the COVID-19 challenge sufficiently, which had implications for the effectiveness of the responses to the pandemic. For example, the implementation of the WHO's recommended active surveillance of cases was affected by the shortage of expert medical personnel, leading to further problems of COVID-19 data management, limited diagnostic capacity, and ultimately, limited institutional capacities (Adebisi, Rabe & Lucero-Prisno, 2021). Besides the limited critical medical expertise in public hospitals, there were further shortages of medical equipment (e.g., laboratory technology, mechanical ventilators), medication, and required infrastructure, which meant that medical centres could not operate at full capacity, especially for the critically ill. In Kenya, for instance, the aggregate intensive care unit beds were only 200, serving the country's 50 million people, translating to a ratio of 1:250,000 (Emejulu, Emejulu & Uche, 2020). In Zimbabwe, the situation got to a point where "patients were turned away as hospitals ran out of capacity to cope with escalating infections and deaths" (MSF, 2021:1). In addition, there were concerns about the health and safety of staff who were working without adequate PPE. Hence, while the WHO guidelines provided the basis for government action, they overlooked the sensitivity to context. Africa became a victim of instrument insensitivities as the recommended WHO COVID-19 containment strategies were incompatible with the region's contextual realities of limited or lack of household income, chronic food insecurity, and restricted access to educational and health services. Africa's unique health sector challenges and the status of the different national health systems called for context-specific response guidelines instead of the one-size-fits-all approach being promoted (Fagbamigbe et al., 2022).

Conclusions

The analysis in this paper attempted to shed light on the role of ineffective policy design in explaining some of the failures in governmental responses to the COVID-19 pandemic by African governments. It is premised on the argument that the design of policy responses to the pandemic constituted policy-making in a crisis context, which, to an extent, explains the design missteps taken by governments. Hence, design-related weaknesses have had a major contributory effect on the ineffectiveness of government responses. The analysis focused on two broad aspects: first, the problematic factors in the African policy design environment, and second, the specific policy missteps that contributed to unwanted social outcomes. At the level of design space or design environment, critical factors discussed include the limited availability of requisite institutional infrastructure and the level of preparedness for managing and containing a health crisis, among others. These greatly affected how much the African governments could do to avert the health crisis. In a way, the combination of these factors complicated things for governments in their policy endeavours. Besides factors obtained in the design environment, the paper identified and analysed the specific policy actions and how they impaired governments' realisation of coherent and effective response actions. The paper concludes that the design of policy responses in contexts of health crises calls for astuteness in navigating inhibitive factors in the design environment and successfully combining policy instruments in a manner that does not generate adverse ripple effects on other sectors. One persisting gap in the literature has been that policies in complex systems often slip into full or partial failure without much clarity of whether the problem is with the design architecture or the environment within which the policies are introduced (van Geet et al., 2021; Hudson, Hunter & Peckham, 2019). This paper contributes towards closing the knowledge gap on policy failure, focusing specifically on the complex context of health crises, using the explanatory strength of the policy design framework. However, the paper does not fully cover the specifics of 'effective policy design', which requires a separate paper to do justice to that aspect.

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Hardlife ZVOUSHE

ORCID ID: <https://orcid.org/0000-0002-3500-2466>

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CHALLENGES RELATED TO ACCOUNTABILITY IN THE SOUTH AFRICAN PUBLIC SERVICE

Shikha Vyas-Doorgapersad

*School of Public Management, Governance and Public Policy; College of Business and Economics,
University of Johannesburg, South Africa*

E-mail: svyas-doorgapersad@uj.ac.za

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Abstract. The study examines the challenges that cause a lack of accountability (focus) in South African public service (locus). Personal greed for financial gain, continuously rising professional status, and demand for authoritative powers are all linked to a lack of personal values that create employee expectations. It is considered corrupt behaviour when achieving personal goals, which involves taking shortcuts through contacts, favouritism, nepotism, and bribery. At the same time, allowing these personal gains to be realised through accepting bribes or giving strategic positions to favoured ones is unethical behaviour. In this scenario, both parties—the giver and the receiver—are being unethical. The study substantiates this situation by compiling information through a document review. This document review was a qualitative study whereby official documents were reviewed to highlight corruption and misconduct statistics. The data was assessed using conceptual and document analysis. The findings reveal a lack of accountability in public service, attributed to a lack of political will to combat corruption, political interference, bureaucratic red tape, and inadequate measures to impose penalties, among other factors. More challenges are discussed in the study. The literature review and analysis of documents assisted the author in proposing a framework called the Accountability Framework for Public Service that suggests measures to enhance accountability and combat corruption at the political, policy, and institutional levels. The framework proposed in the study can be considered an inductive contribution to public administration, management, and governance.

Keywords: accountability; corruption; qualitative study; misconduct; public service; South Africa

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JEL Classifications: D73, H83

Additional disciplines: Development Studies, Public Management.

1. Introduction

The supreme abiding document, that is, the Constitution of the Republic of South Africa (1996), establishes the concepts of accountability and monitoring across all the spheres of government (Munhendzi, 2016:1). The constitutional mandate to provide public services applies to all three government tiers, and each sphere's capacity determines its level of responsibility and public service rendering. Public authorities are under greater scrutiny for demonstrating accountability while using the resources at their disposal. Administrators in the public sector are increasingly relying on internal audits and audit committees to ensure responsibility and prudent financial management (Ngumbela, 2022:2). Accountability requires exposing, explaining, and justifying behaviours (Van der Nest, Thornhill & De Jager, 2008:546). It requires that public organisations make their operations public to foster open conversation and critique (Vyas-Doorgapersad & Ababio, 2006:393). Similarly, Mamokhere (2020) agrees that accountability is essential for a sound government. As a result, accepting responsibility is a requirement of public accountability, as suggested by Kgobe and Mamokhere (2021:3).

Despite several legislative frameworks put in place to promote accountability in the public sector, evidence from practice demonstrates that the process of promoting accountability has never been smooth. Accountability, in the context of this study, refers to promoting sound administration in the public sector by eliminating corruption, increasing the efficient functioning of the public service sector, and preventing individuals in positions of power from abusing their authority. According to Pedersen and Nielson (2016:361), holding government officials accountable for their actions enables punishing those who engage in unlawful conduct and discourages others from engaging in illicit activities. The Zondo Commission established that contrary to this norm, there is an inadequate level of responsibility in the South African public sector, which has provided opportunities for corruption. Failure to properly hold top government officials accountable has resulted in the misuse of government resources and acts of fraud (Wille, 2016:700). Ubisi (2018) further notes that a lack of public accountability hinders service delivery in South Africa.

Various studies have been conducted to explore misconduct in the service delivery sectors. Maile (2022) investigated corruption and misbehaviour with a micro-level concentration in a chosen national government department. Future research by other scholars could cover other public service departments in South Africa as comparative studies (macro-level). The results indicated that the most efficient way to reduce corruption and nepotism could be to set up oversight agencies. Establishing an ethical culture requires adherence to the King Reports and Codes. The conceptual frameworks for effective governance and organisational ethical management were thoroughly explained in the study. To foster an ethical culture within the Local Government Sector Education Training Authority (LGSETA), a study by Mothabi (2022) followed the fourth King Code of Corporate Governance, also known as King IV. With a focus on ethics and ethical culture, the study offered insights into the conceptual frameworks related to King IV.

Mlambo, Mpanza, and Simangele's (2023) study examines the conflict between corruption and governance in South Africa's public sector. To address the central question of this study, it conceptualises the concept and origin of good governance and uses a narrative literature review. According to the report, corruption has plagued South Africa for years, wasting billions of government dollars through wasteful spending. According to a study by Sithomola (2024), the decline of good governance, socioeconomic development, and public trust in public institutions has been further exacerbated by corruption and unethical behaviour among public personnel. South Africa's campaign against corruption has become a symbolic endeavour that has not produced the desired results, despite its adherence to compliance or rule-based ethics. The article's main conclusions show that results are not assured by simply implementing a compliance-based public sector. Only when consequence management is implemented through robust institutions that are not influenced by the political climate can the rule-based approach produce the desired results. According to a study by Dhlamini (2025), until the country focuses on the precise location and mode of financial misconduct and corruption, it will be hard to eradicate these issues in the South African public sector. By examining corruption in state-owned enterprises, the study concentrated on the areas of the government where corruption takes place. Since SOEs provide essential commodities and services in critical economic sectors, many citizens' basic needs go unmet in this corrupt government sector. The report covered Eskom, the biggest state-owned enterprise (SOE) in South Africa, and the parastatal's numerous financial mismanagement and corruption over the years, leaving it unstable and hard to maintain (Dhlamini, 2025). The literature analysis demonstrates that, with emphasis on the public service sector, the aspects of misconduct and corruption are continuously investigated and addressed in a South African setting. However, there isn't a thorough explanation of the specific accountability component.

The study aims to close this gap by concentrating on the elements that make it more challenging to carry out accountability effectively, making it more difficult to combat misbehaviour and corruption in the public sector.

Despite 30 years of democracy, South African public service faces significant public accountability and malfeasance challenges. According to Munzhedzi (2016:6), South Africa continues to face numerous issues because of a lack of accountability. This suggests that accountability in the South African public sector is compromised (Sindelo, 2024:1).

The article discusses the areas where accountability challenges are witnessed, factors impeding the successful execution of accountability, and, hence, the prevalence of corruption in South Africa. It also proposes recommendations for improvement.

2. Accountability Challenges in South African Public Service

Most government institutions have been grappling with enforcing effective and efficient accountability mechanisms. It is essential to delve into some key areas where accountability challenges are prevalent in the public sector. Financial transgressions were documented in the 2016/17 fiscal year, including irregular expenditure, financial misconduct, misappropriation and misuse, theft, fraud, unapproved spending, and corruption. Government departments at the national level reported more cases resolved than provincial government departments, according to the Public Service Commission (PSC) Report (2017, 2020, 2023; Maile, 2022:65).

Figure 1 below depicts the quarterly trend analysis of alleged corruption from the 2017/18 to the 2020/21 financial year.

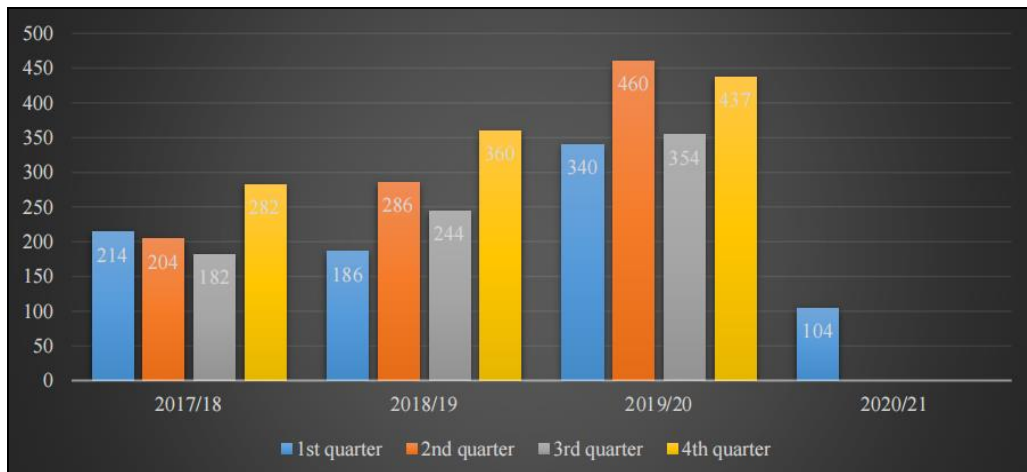


Fig. 1. Trend Analysis of Cases of Alleged Corruption Recorded from 2017/18 to the 2020/21 Financial Year
Source: PSC, 2020:16; Maile and Vyas-Doorgapersad, 2023:12

Figure 2 shows the total number of misconduct instances reported by national departments between 2017/18 and 2020/21.

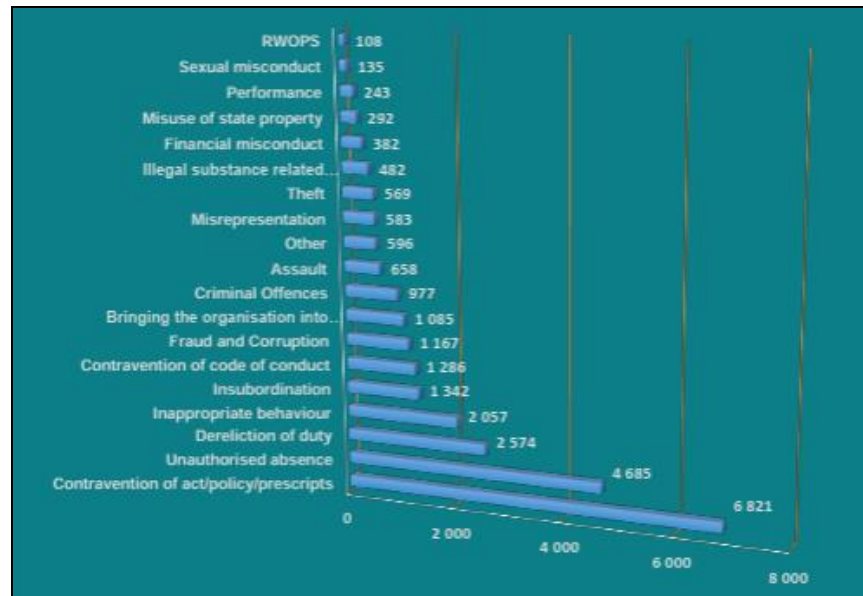


Fig. 2. Cumulative Misconduct Cases for National Departments (2017/18 to 2020/21)

Source: PSC, 2022:8

Note: the figure is copied from the PSC 2022 document. There are some incomplete explanations on the y-axis in the figure.

The full description is stated here as: RWOPS stands for Remunerative Work Outside the Public Service;

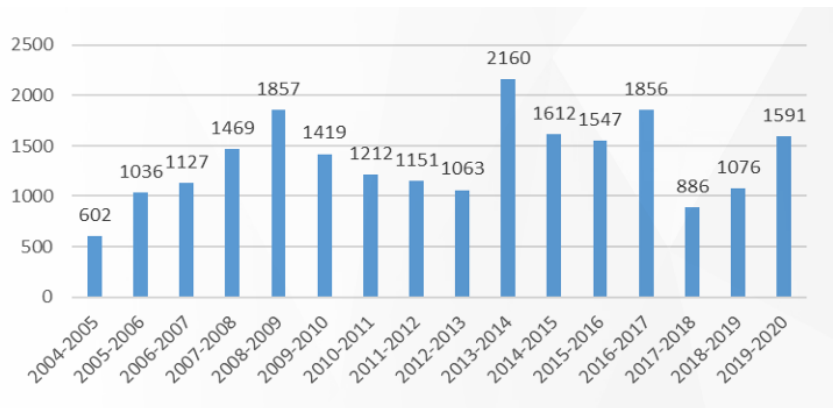
Illegal substance related transgressions; and Bringing the organisation into disrepute.

Figure 2 depicts the varying pattern of *contravention of act/policy/prescripts* incidents over four years, indicating that public service policies and guidelines are being disregarded. It is concerning when the same misbehaviours keep happening over time because it either indicates poor consequence management or a lack of required leadership (PSC, 2022:8). Inadequate internal controls may also be a factor in the increasing number of *conventions of act/policy/prescripts* situations. Most of these cases involved the South African Police Service (SAPS) and the Department of Correctional Services (DCS). Common violations for the DCS and SAPS included breaking of security measures, participation in unprocedural, unprotected, industrial action, non-disclosure of financial interest, and releasing a prisoner without proper authority; however, it was unclear which prescripts were broken in particular situations (PSC, 2022:8).

The Corruption Watch 2021 Annual Report reports many forms of misbehaviour. The following are some of the misbehaviour figures highlighted in the report, summarised by the author (Corruption Watch, 2021: 31; Vyas-Doorgapersad, 2022: 16):

- Maladministration (highest) (18%)
- Corruption in procurement (second highest) (16%)
- Misuse of power (also second highest) (16%)
- Fraud (high) (14%),
- Resource theft (second high) (12%)
- Neglect of responsibilities (significant to reduce) (8%)
- (8%), bribery or extortion (significant to combat) (8%)
- Corruption in employment (significant to correct) (8%)

The trend of continued corruption patterns recorded from 2004 till 2020 is stated in Graph 1.



Graph 1. Cases of alleged corruption since the inception of the National Anti-Corruption Hotline (NACH) from September 2004 to March 2020
Source: PSC, 2020; Vyas-Doorgapersad, 2024a: 456.

Lack of accountability could be a significant factor. Accountability is directly related to responsibility for decisions, actions, outcomes, and policies. Effective execution, moral leadership, integrity-driven management, and clean government are synonymous with accountability. Each person in the public service pyramid has clearly defined responsibilities for each job position, or they should be required to take responsibility for the performance, inputs, outputs, and results of their operations (Pillay, 2016:116; Vyas-Doorgapersad, 2024a:457). In addition to the existing legislative bodies, rules, and laws, elected officials cannot be held politically accountable if they do not listen to, value, and respond to the people. Accountability refers to the obligation of those in positions of power to defend, justify, and take ownership of their decisions, actions, and results. Administrators must behave according to the commitments and requirements outlined in laws, regulations, guidelines, procedures, and policies, as emphasised by Vian (2020:2) and adapted by Vyas-Doorgapersad (2024a:457). While not always a sign of corruption, failing to hold people accountable suggests a pattern or, at the very least, a sign of possible issues. There are powerful incentives to keep corruption hidden, particularly when it involves influential individuals or groups (Sole, 2005:87). The section below explores accountability challenges in specific areas as part of the study.

2.1 Financial Management

Financial misconduct in the public sector is well documented. PSC (2023: 13) statistics for all national departments from the 2013/2014 and 2021/2022 financial years reveal several financial misconduct cases, with the number of instances fluctuating over that period. Nevertheless, the amounts involved seem to be gradually increasing, with the most excessive amount being R999,095,598 in the 2021/22 fiscal year, with only 235 cases across all national ministries and only 8% legally accused (PSC, 2023: 13). Only R174,532 010, or 5.4%, of the R3,211,610,817 lost by the state due to financial wrongdoing has been recovered, while R1,847,057,816, or 58%, remains unrecovered (PSC, 2023:13).

One of the challenges identified in the literature relates to a lack of skills and capacity among public sector employees. Inadequate talent is one of the key variables influencing the performance of public sector financial management. According to Abdulai, Salakpi, and Nasse (2021:4), staffing deficiencies can lead to poor management, errors, and hostility in certain circumstances. Furthermore, Abdulai et al. (2021:4) state that adequate staffing and workforce management are crucial to effectively executing internal auditing. However, some officials nominated to critical positions do not meet all the standards and lack the essential skills to perform their duties (Abdulai et al., 2021:6). According to Dodo (2017:19), a lack of technical experience and financial auditing skills is a major contributor to audit committee ineffectiveness. This problem has become more prevalent in local government settings.

According to the Auditor General of South Africa (AGSA) (2021:8), local governments depend on consultants to prepare financial accounts and examine underlying data for significant accounting discrepancies. Over R1 billion was spent on consultants for financial reporting services during the 2019/20 fiscal year (AGSA, 2021:8). Consequently, the complex difficulties continue to hinder management's ability to conduct timely, creditable audits. The AGSA (2021:8) further states that insufficient training, limited skill sets, inexperienced auditors, vague audit objectives, poor report writing abilities, and demotivation have all contributed to the low calibre of the work.

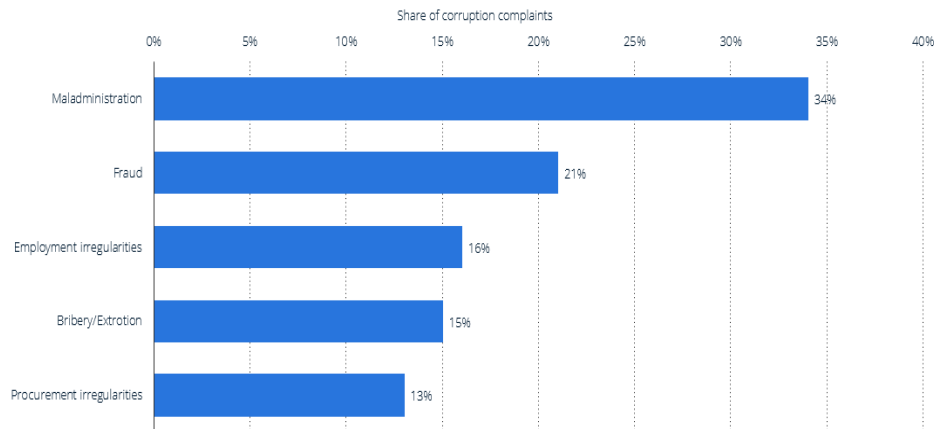
A lack of consequence management is one of the challenges impeding effective financial management. According to Abdulai et al. (2021:6), auditing staff spend an extended period reviewing numerous records and other material, negatively impacting productivity. As a result, Abdulai et al. (2021:6) note that auditing encounters difficulties, such as fake financial reporting and audit failures. Furthermore, audit committees lack the jurisdiction to summon government departments for poor performance or failure to submit required financial statements on time. As a result, the committees have limited options and their requests for data are routinely denied. It is noted that this significantly affects their capacity to provide the council with timely financial and institutional performance reports (Toxopeüs, 2019).

Rampant corruption in the public sector has also hindered sound financial accountability. The study shows corruption increases when public sector organisations lack adequate financial monitoring. Corruption Watch has received more than 5,000 reports of misconduct in the public sector since its establishment in 2012 (Corruption Watch, 2021:1). These investigations provide a disturbing overview of how some government agencies have been seized for personal gain, how local officials misuse their authority and position, and how hiring and procurement procedures are regularly compromised. This prevents disadvantaged populations from accessing essential services and human rights (Corruption Watch, 2021:1).

2.2 Procurement

Public sector procurement practices and systems have been scrutinised since the new democratic dispensation in South Africa. Evidence suggests that the Lack of accountability has exacerbated supply chain management and procurement challenges. One of the documented challenges relates to weak enforcement of procurement legislation, which results in repeated procurement violations (Simone & Balasundharam, 2023: 1). While this is partly due to the fractured statutory and regulatory environment, organisations' inability to implement rules governing procurement is also a significant issue. According to Simone and Balasundharam (2023: 1), suppliers take advantage of enforcement flaws, resulting in repeated violations such as extortion, favouritism, conflicts of interest, collusion and bid rigging, misuse and manipulation of data and procedures, and waste and misuse of public funds.

According to the 2020/21 Auditor General report, an unfair and insufficiently competitive procurement process is the most frequent procurement complaint, even in enterprises with clean audits. Government agencies' adoption of suitable procurement procedures and ability to sufficiently justify exclusions from competitive procurement are other issues (AGSA, 2021:5). Graph 2 shows that corruption in procurement practices is one of the prevalent forms of misconduct and requires corrective measures.



Graph 2. Prevalence of National Corruption in South Africa as of 2023 by Type
Source: Corruption Watch (2023); Statista (2024); Vyas-Doorgapersad (2024b:87)

Limited transparency across the different phases of public procurement encourages misconduct (Nzimakwe & Biyela, 2021). Transparency in government contracting not only improves honesty, promotes accountability, and assists in preventing misconduct, thereby fostering confidence in government entities, but it also plays a substantial part in levelling the playing field among companies and permitting small and medium-sized enterprises to get involved in an equal footing (PSC, 2023:14). Nevertheless, without a complete listing of all tenders that have been bid on for the fiscal year 2022/23, it is impossible to ascertain that all tenders were posted (PSC, 2023: 14). The same passion for promoting bids is not shared for publishing details regarding granted tenders because the necessary detail on awarded bids is rarely expressed on both the e-tenders portal and departmental websites, which limits accountability. Procurement contributes significantly to the growth of South Africa's economy and is crucial for the effective delivery of government services. Nevertheless, citizens and taxpayers do not receive adequate value for their money because this region is prone to waste and corruption. A lack of respect for the profession has culminated in a shortage of strategic talents in supply chain management (Nzimakwe, 2023:14). It has been noted that one of the key difficulties in South Africa's government and government-owned businesses remains the Lack of a suitable skilled and capacitated workforce, particularly in supply chain management (Nzimakwe, 2023:14).

2.3 Political Accountability

The concept of political accountability in the context of South African public service demonstrates numerous issues that jeopardise accountability, openness, and confidence among citizens. These issues stem from historical, organisational, and socioeconomic causes. It is worth noting that corruption and maladministration in the public sector have hindered political accountability. The occurrence of state control, in which wealthy individuals exert excessive influence over the choices made by governments, has significantly damaged measures to improve accountability. Prominent examples, such as those disclosed by the Zondo Commission of Inquiry into State Capture, include systematic misconduct in procurement procedures, government-owned companies, and even law enforcement (Zondo Commission Report, 2022). Furthermore, criminal activity and the theft of taxpayer monies siphon resources intended for providing public services, undermining confidence in the government. Notwithstanding the presence of corruption prevention organisations such as the Special Investigating Unit (SIU) and the Public Protector, execution is sometimes sluggish or inefficient because of heavy political involvement and limited resources (Transparency International, 2023).

Evidence also points to the reality that weak institutional frameworks have undermined political accountability in public service. According to the Organisation for Economic Co-operation and Development (OECD) (2022), several government institutions lack the capital, competencies and expertise needed for successful oversight and

accountability enforcement. It can be documented that the involvement of politicians in the main activities of key accountability agencies, such as the National Prosecuting Authority (NPA) and the South African Revenue Service (SARS), has weakened their sense of autonomy and independence (Institute for Security Studies, 2021). Moreover, evidence also points to disjointed or fragmented supervision systems, with multiple roles and insufficient collaboration among key entities, such as the Public Protector, Auditor General, and Parliament, undermining the aggregate efficacy of holding government officials responsible (Public Protector South Africa, 2023).

Nepotism and political patronage have played a devastating role in undermining accountability in the South African public sector. The deployment of cadres, in which the party in power assigns loyalists to critical governmental positions, has been widely condemned for prioritising ideological allegiance over ability and performance (Institute for Security Studies, 2021). This is further explored by Adanlawo and Chaka (2024: 266), who argue that cadre deployment compromises the government's efforts to promote sound financial management and accountability, especially in the local government setup, in which elected officials dominate.

Meaningful community participation is essential for keeping government officials accountable, but the country faces significant obstacles. Low levels of public engagement, particularly among vulnerable populations, often result from a lack of information or access to procedures for accountability (OECD, 2022). Additionally, widespread disdain for government institutions deters citizens from engaging in oversight mechanisms. Consequently, minimal political and educational initiatives result in many South Africans being uninformed of their constitutional entitlements or how to hold authority figures accountable (South African Human Rights Commission, 2022).

3. Research Methodology and Theoretical Framework

The study aims to identify accountability challenges in South African public service. The research questions, therefore, are: What are the accountability challenges in public service? What are the factors that are impeding the effective implementation of accountability? What are the policy recommendations to ensure accountability in a country-specific context?

Non-numerical textual, visual, or auditory data was gathered and analysed to address the research questions and accomplish the study's goals, making the study qualitative. Qualitative research is frequently used in the humanities and social sciences. It is done to gain a comprehensive understanding of a problem, to generate new research ideas, or to comprehend experiences, ideas, or points of view, as suggested by Bhandari (2020:1) and adapted by Maile (2022:8). Denzin and Lincoln (2005, cited in University of Southern California, 2018:1; and considered by Bangani, 2019:9; Maile, 2022:8-9) further emphasise that qualitative researchers emphasise the close interaction between the researcher and the study subject, the social construction of reality, and the influence of environmental restrictions on research. These academics emphasise how inquiry is a value-laden process. The problems they seek to solve focus on how social experiences are constructed and interpreted.

The information was compiled using a document review. First, since data is frequently publicly available, modern researchers often avoid the time-consuming procedure of obtaining formal authorisation to contact participants, and they do not require authorisation to view secondary materials (Jensen et al., 2022:1149). Second, document evidence is frequently accessible in software-compatible formats, such as spreadsheets, which researchers can readily enter into contemporary data analysis tools (Saunders & Lewis, 2018:94). Third, because document reviews are nonintrusive, they do not require direct respondents or the laborious procedure to gather data (Pederson et al., 2020:59). Fourth, researchers can easily synthesise documentary evidence into a single, comprehensive report by combining several secondary document data sets from surveys or other studies (Pederson et al., 2020:59). This approach adds to the documentary evidence's authentication process by allowing

the public to examine it further (Saunders & Lewis, 2018:95). Last but not least, documentary material facilitates contemporary research by offering a contextual backdrop, which makes it simpler to generate unique discoveries (Pederson et al., 2020:59). Consequently, the study employed a document review to enhance the findings' credibility and provide more context. Official South African government papers were among the documents examined, such as reports from the Public Service Commission, Transparency International, Corruption Watch, Statista, Auditor General reports, and legislative Acts and frameworks.

The process of fitting a study to a specific framework that gives meaning to a large amount of gathered data is known as qualitative data analysis (Alyamahdy & Alabri, 2013:1; Mothabi, 2022:10). Both document and conceptual analysis were used to analyse the data for this investigation. Vyas-Doorgapersad and Nyikadzino (2020:236) indicate that critically examining a substantial amount of written content is part of document analysis.

One popular framework in the study of societal accountability is the principle-agent theory. It is essential because it offers a versatile framework for simulating a variety of institutional contexts and evaluating the probability that certain institutional arrangements will persuade actors to behave as planned (Gailmard, 2014:91; Dhlamini, 2025:25). Adam Smith offers one of the earliest explanations of the principal-agent phenomena in his book *The Wealth of Nations*. He describes a corporate structure wherein proprietors, or owners, designate or hire managers or agents to run their businesses on their behalf (Smith, 2005:96; Dhlamini, 2025:25). This theory looks at partnerships where one party (the principal) gives another (the agent) responsibilities so that the agent can act on behalf of the principal. The government is the leading actor in government-public servant partnerships, designating workers as agents in the execution of policies meant to promote the development of human capital (Kofar-Sauri, 2023:3; Dhlamini, 2025:25).

4. Discussion and Findings

Based on the findings, this section discusses factors that impede the effective implementation of accountability and cause corruption in South Africa. Corruption in South Africa is a malignancy that has consistently hindered socioeconomic progress, poverty reduction, and effective governance in the nation. Multiple studies by various organisations regarding South African citizens' views on corruption reveal an escalating belief that the government is ineffectively addressing corruption, which is progressively worsening despite numerous initiatives implemented to mitigate it. According to Ntoyanto (2019:1), South African political role-players have responded to national and global expectations and pressure to mitigate increasing corruption in the public sector in the last decade. This has resulted in the creation of various legislative measures, specialised investigative task forces, committees, units, and commissions of inquiry. Most of these are established individually, resulting in no charges or penalties for the culpable parties. Numerous monitoring organisations and citizens have articulated concerns that the overt impunity to senior civil personnel erodes accountability and fosters corruption.

South Africa achieved democracy in 1994; despite this milestone, corruption continues to escalate in both the public and commercial sectors. Since 1994, South Africa's shift to a nonracial democracy has been marred by recurrent occurrences and accusations of governmental corruption, implicating elected leaders and civil personnel (Naidoo, 2013:522). The public is inundated with weekly media coverage of fresh and longstanding corruption reports. Corruption in the public sector typically arises from public officials exploiting their positions for personal benefit (Naidoo, 2013). The persistent issue within the public sector is corruption, which indicates that instances of unlawful and unethical conduct by politicians and public servants are a persistent characteristic and an inherent risk within the public sector (Naidoo, 2013). This risk obstructs sustainable development, foreign direct investment, service provision, and poverty reduction. Corruption poses a significant danger to the nation's development for several reasons. Over the past twenty years, the government has enacted various anti-corruption measures. These strategies have produced limited outcomes (Budhram & Geldenhuys, 2018; Gray, 2021). The recent misuse of the COVID-19 relief fund, testimony regarding tender discrepancies, scandals at the Ministry of

Health, and the killing of a whistleblower in the Gauteng Health Department indicate that corruption remains endemic in the country (Patel & Govindasamy, 2021).

Over the past decade, multiple commissions have been established to investigate allegations of corruption and misconduct by government officials. Additional investigation units have been established in accordance with suggestions from the Office of the Public Protector and Parliament. These inquiries and commissions of inquiry have revealed fraudulent activities involving multiple government officials, including former president Jacob Zuma. Allegations of corruption against Zuma emerged before his presidency, continued throughout his tenure, and persisted until the conclusion of his administration (Labik Amanquandor, 2024; Gray, 2021). Corruption at elevated echelons, including that of the president, undermines societal morals and perceptions of corruption. Corruption in the public sector primarily involves individual government officials, business owners, and the ruling party. Government officials affiliated with the ruling party provide preferential treatment to company owners, who, in exchange, offer favours to the ruling party or compensate the particular public official. When inquiries are initiated to expose these unethical practices, corrupt public officials obstruct those probes (Ntoyanto, 2019: 2).

The primary issue in combating and eliminating corruption in the public sector has been the absence of consequence management for individuals accused of corruption and the inconclusiveness of corruption cases (Manyaka & Nkuna, 2014). Corruption cases may persist for years without a definitive resolution. Numerous public officials in South Africa have evaded prosecution. The Lack of accountability perpetuates a culture of corruption that increasingly becomes normalised because anti-corruption authorities function more as watchdogs than guard dogs.

The second challenge arises from political interference, which affects the ability of anti-corruption institutions to conduct investigations. Former employees of the Scorpions expressed concerns that the dissolution of their essential crime investigation unit, subsequently replaced by the Hawks, was intended to shield influential members of the ruling party under investigation at the time (Naidoo, 2013). The unit was established following decisions made by the African National Congress (ANC) at its 52nd National Conference. Naidoo (2013) argues that the ANC advocated establishing such a unit in response to increasing corruption. This example illustrates the influence of politics, as a decision made by a political party during its conference resulted in the establishment of a specialised unit. The complexities of political meddling and the politicised nature of anti-corruption in South Africa are significant. [There is] no evidence that the structure of institutions may overcome this problem, given the notable efficacy of collective political actions. It can be assumed that top political leaders' commitment, willingness, and ethical conduct will enhance the effectiveness of anti-corruption enforcement in South Africa (Mphendu & Holtzhausen, 2016). The third difficulty pertains to the functions of commissions of inquiry and the judiciary. Commissions of inquiry lack binding authority over their conclusions and recommendations and the capacity to impose penalties on the culpable (Ntoyanto, 2019: 3).

Commissions of inquiry are authorised solely to provide recommendations to the individual who initiated the panel, typically the president. Furthermore, these recommendations are grounded in the scope of their investigation. Commissions of inquiry are often established by terms of reference pursuant to Section 84(2)(f) of the Constitution (Ntoyanto, 2019: 3). According to Section 1 of the Commissions Act, 1947 (Act No. 8 of 1947), the president proclaims the provisions of the relevant Act concerning the commission and establishes regulations pertinent to it. The commission possesses the authority to exercise procedural discretion during the investigation process and to choose the desired level of confidentiality for the inquiry (Ntoyanto, 2019: 3).

In the context of local governance, April and Sebola (2016) note that the appointment of senior officials predominantly relies on political connections and employment equity. The Lack of meritocracy has resulted in numerous departments being led by ineffective leaders who fail to implement the nation's anti-corruption laws and

policies, thus fostering institutional settings that reinforce unethical and nepotistic behaviour (Majila et al., 2014; Manyaka & Nkuna, 2014). Public administrators must embody their organisation's code of conduct and professional standards in their daily behaviour to enhance the ethical climate of their workplaces (Parboteeah et al., 2014). Unfortunately, several public sector agencies in South Africa are managed by unethical leaders who exploit systemic loopholes for personal benefit (Odeku, 2019:11). Bribery and corruption exist even among the highest levels of the country's anti-corruption enforcement agencies (Olutola, 2014).

South Africa's anti-corruption institutional framework is underpinned by a comprehensive array of laws, rules, and regulations, establishing approximately 19 institutions, agencies, and coordinating mechanisms (Pillay, 2017). Dassah (2014) identifies that the country's model is plagued by the inherent weaknesses of the multi-agency framework, including red-tapism, patronage networking, and inter-agency rivalry.

The mandates of anti-corruption agencies are ambiguous and overlapping, prompting some analysts to contend that the model suffers from inadequate oversight, coordination, a cohesive strategic framework, and a central principal agency (Chetty & Pillay, 2017; Pillay, 2017). Based on the findings, the study proposes an analytical framework called the Accountability Framework for Public Service (see Figure 3).

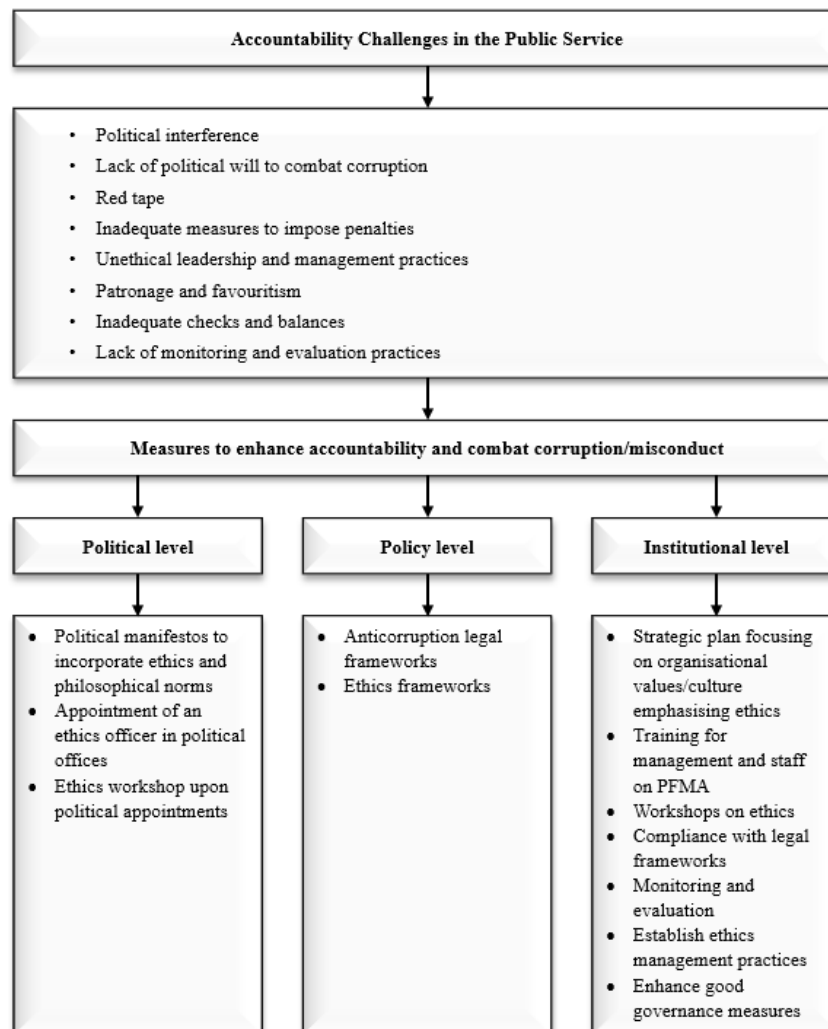


Figure 3. Accountability Framework for Public Service

Source: Author's compilation based on secondary information, 2025.

Based on the challenges explored in the study, the article proposes that specific measures are required to enhance accountability and combat corruption and misconduct in the public service. These measures are suggested at three levels: political, policy, and institutional. *At the political level*, it is imperative that political parties incorporate ethics and philosophical norms in their manifestos. Since ethics and concern for the inner world, rather than the outer, became the main focus of thought and inquiry in the fifth century BC, it is important to note that Socrates, who is considered the founder of moral philosophy, is credited with the pivotal moment that marked the shift in philosophy from physics to ethics (Makrydemetres, 2002:3; Vyas-Doorgapersad & Ababio, 2006:386; Vyas-Doorgapersad & Simmonds, 2011:58). Ethics is a natural concern when discussing the actual role of politicians and state administration, but it is rarely brought up in ideological debates about the state's purpose. Public officials and politicians both have discretionary authority; their choices have a significant impact on a large number of people. Therefore, some form of ethics should guide these decisions (Amundsen & de Andrade, 2009: 10-11; Maile, 2022:22). Concerns about the general processes of the globalisation of market economies and information technology, as well as the localisation of political conflict, authority structures, and culture, are the issues that public administration practitioners and scholars face in many countries. To achieve good governance, these developments spark discussions about how ethics are applied at different levels of authority (Vyas-Doorgapersad & Ababio, 2010:412-413; Maile, 2022:22-23). The article's stated incidents violate public administration norms; hence, according to Vyas-Doorgapersad and Simmonds (2011:56), as cited by Mothabi and Vyas-Doorgapersad (2022:369), to establish an atmosphere of excellent corporate governance, public administration must collaborate with the normative instruments of integrity, honesty, and ethics. This requires a normative approach to instil ethical public administration and management frameworks. Vyas-Doorgapersad and Shava (2021:45-46) and Mothabi and Vyas-Doorgapersad (2022:369) suggest that, consequently, the successful application of moral principles leads to the development of a value-driven public administration. Hence, it is recommended that political parties adopt normative values and align their ideologies with ethical principles. Incorporating ethics in manifestos may also foster trust among voters when they see their representatives abiding by moral principles and values. Voters may also view their political representatives as role models and adopt their moral values on both personal and professional fronts. This may seem hypothetical; however, charismatic leaders can establish an ethical path for people to follow, but this takes time, courage, and strength. It is significant to note that good governance always has the upper hand over maladministration when public administration processes, systems, and structures are enveloped with normative principles and become an abiding force for role-players. At the political level, it is also suggested that political parties appoint an ethics officer to oversee the internal governance processes. The ethics officer can offer guidance regarding the consequences of misconduct and inform party members to remain ethical in dealings and behaviour. The ethics officer may organise workshops to inform party members about ethical frameworks. Such workshops may be organised with political appointments so that members can be equipped with a moral understanding of processes and dealings as they commence their political journey.

At the policy level, it is suggested that anti-corruption laws and ethical frameworks be established for public servants. The Constitution of the Republic of South Africa (1996) emphasises that high standards of professional ethics be maintained. The other legislative frameworks listed here are the Public Entities Act, No. 93 of 1992, the Public Service Act, No. 122 of 1994, the Investigation of Serious Economic Offenses Act, No. 46 of 1995, the Employment Equity Act, No. 55 of 1998, the Executive Member's Ethics Act, No. 82 of 1998, the Public Finance Management Act, No. 1 of 1999, the Promotion of Administrative Justice Act, No. 3 of 2000, the Protected Disclosures Act, No. 26 of 2000, the Public Audit Act, No. 25 of 2004, the Prevention and Combating of Corrupt Activities Act, No. 12 of 2004, and the Public Administrative Management Act, No.11 of 2014 (Maile, 2022). These Acts guide public servants to act ethically and morally in all their professional dealings.

At an institutional level, it is recommended that the ethical norms established at the political and policy levels be implemented to create an environment of good governance. This requires strategic role-players to ensure their organisational/business plans focus on the organisational values of honesty, transparency, accountability, and

ethical principles. Staff must receive continuous training under the PFMA. The human resource manager or labour relations manager may schedule workshops on ethics for all new appointees to understand the consequences of misconduct and the importance of adhering to the ethical culture in the workplace. Staff must adhere to legislative frameworks discussed at the policy level, and compliance must be documented. Monitoring and evaluating organisational structures, systems, and processes are required to ensure that all checks and balances are in place and that oversight mechanisms are effective. It is suggested that public service must have organisational ethics management (OEM) procedures in place. OEM gives businesses the ability to control and guide workplace ethics. These programmes must establish educational and ethical standards as well as decision-making methods. Staff members must understand these standards, and those who practice ethical management must be diligent in monitoring and evaluating employee morale. The first step in the ethics management process is to develop a collection of essential principles that specify the organisation's ethical charter (Hamid & Nezhad, 2014: 9956; Vyas-Doorgapersad, 2022:22). Considering the views of Vyas-Doorgapersad and Simmonds (2011), Thonzhe and Vyas-Doorgapersad (2017: 146) suggested that these principles provide the basis of responsible and accountable behaviour at all levels of government when combined with values and morals. To think logically and be dedicated, policymakers and public managers benefit from employing philosophical tools which use a normative approach. These measures help establish an environment of good governance, characterised by accountability, transparency, honesty, effectiveness, and efficiency, and combat corruption and misconduct in the public service.

5. Conclusion

The study's limitation is its Lack of empirical evidence. The topic is sensitive, and conducting interviews with public service employees may not have been successful. Obtaining ethical clearance to conduct interviews in the public service departments may have been rejected on the grounds of protecting the organisational image. Employees are also expected not to divulge confidential information, which is against work ethics. Consequently, the author maintained research ethics and scholarly decorum, focusing on compiling information from publicly available sources. Future studies may use a qualitative desktop analysis to explore the accountability challenges in the selected public service departments. This may become part of a longitudinal and comparative study, contributing to public management, ethics, and development studies.

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Shikha VYAS-DOORGAPERSAD is a Full Professor, School of Public Management, Governance and Public Policy at University of Johannesburg, South Africa. Her previous lecturing experience includes International College for Girls (India); University of Zululand, and North-West University (South Africa). She holds degrees of M.A., M.Phil., and Ph.D. in Public Administration from the University of Rajasthan (India). She has presented research findings at international conferences worldwide. She has authored two books (University Book House, Jain Prakhn Mandir [Publishers in India]), Editor of three books (Taylor and Francis, Routledge [Publishers in New York]); contributed chapters in books and have published articles in national and international accredited journals. She serves as Editor-in-Chief, Guest Editor, Associate Editor, Editorial Board Member, and reviewer to South African and international journals. She is a member of the International Advisory Board and International Scientific Committees at various conferences worldwide. She is serving as an Adjunct Research Professor in the School of Business and Management of Uganda Technology and Management University. She is appointed as a Visiting Professor at the Riara School of Business, Riara University in Kenya. She serves as External Moderator/Examiner for MAs and PhDs for several universities in South Africa. She has published more than 150 articles in scientific journals. Research interests: Her research interests are in Public Policy, Gender Issues, and in Municipal Governance.

ORCID ID: <https://orcid.org/0000-0002-8146-344X>

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EXPERIENTIAL MARKETING AND ITS EFFECTS ON CUSTOMER E-SATISFACTION AND CUSTOMER HAPPINESS WITH ONLINE PURCHASES IN MTHATHA

Lucas Vukethwele ^{1*}, Siphonathi Fihla ², Richard Chinomona ³

^{1*,2,3} Department of Economics and Financial Science, Walter Sisulu University, South Africa

^{1*,2,3} SEEDS, Department of Economics and Financial Science, Walter Sisulu University, South Africa

E-mails: *¹lvukethwele@wsu.ac.za (Corresponding author); ²sfihla@wsu.ac.za; ³rchinomona@wsu.ac.za

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Abstract. The late 1990s and early 2000s saw the rise of electronic commerce as Internet access became more widespread, leading to the emergence of new online business models. Today, customers can access a wide range of brands offering similar products or services at comparable prices and quality levels, making e-satisfaction a crucial factor in customer happiness. However, other factors also affect overall satisfaction, with e-satisfaction closely linked to these elements. This research aims to investigate the influence of experiential marketing on customer e-satisfaction and happiness with online purchases in Mthatha. Following a positivist research paradigm, the study employs a quantitative approach with a cross-sectional design, distributing a fully structured self-administered questionnaire to 314 fashion industry customers in Mthatha. The methodology allows for the systematic collection of numerical data to analyse the relationship between experiential marketing and online purchase behaviour, to provide measurable insights into the impact of experiential marketing on consumers' purchasing decisions and inform business strategies within the fashion sector.

Keywords: sense experience; think experience; feel experience; act experience; relate experience; customer e-satisfaction; customer happiness; South Africa

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JEL Classifications: M3, M31

1. Introduction

According to Kanaan and Pathmanathan (2021), experiential marketing has emerged as a dynamic and innovative approach for brands to connect with consumers in an increasingly digital world. Unlike traditional marketing strategies focused solely on product features and benefits, experiential marketing aims to create memorable and immersive brand experiences that resonate with customers on a deeper level. By engaging multiple senses and emotions, experiential marketing seeks to forge stronger emotional connections between consumers and brands, ultimately leading to increased satisfaction and happiness with online purchases (Pathmanathan et al., 2021; El-Ebiary et al., 2021).

In recent years, the rise of e-commerce has revolutionised consumer shopping habits, creating new challenges and opportunities for brands. Online shopping offers convenience and accessibility but lacks the traditional stores' sensory experience. Experiential marketing addresses this gap by providing virtual experiences replicating the excitement and engagement of in-person shopping, bridging the physical and digital worlds.

Enhancing the online buying experience is one of experiential marketing's primary benefits on customer e-satisfaction (Ehsani & Hosseini, 2023). Brands may make the shopping experience more interesting and pleasurable for customers by using interactive elements like immersive storytelling, personalised product recommendations, and virtual try-on tools. Brands may stand out in a crowded market and forge closer bonds with consumers by providing distinctive and unforgettable experiences. This will increase customer satisfaction with online purchases.

Customer satisfaction with online transactions is significantly impacted by experiential marketing. Experienced marketing initiatives can arouse emotions like happiness, excitement, and fulfilment by reaching out to consumers' emotions and desires. A cosmetics company might, for instance, develop engaging online beauty instruction that gives users confidence and empowerment in addition to education. Brands may create a sense of consumer satisfaction and fulfilment by providing value beyond the transactional exchange. This will eventually encourage advocacy and loyalty (Khan, Zubair, & Malik, 2019).

Experiential marketing surpasses traditional advertising methods by creating immersive encounters that evoke emotions and resonate with consumers personally. These experiences can influence purchasing decisions, shape long-term brand perceptions and foster loyalty. By engaging customers in memorable experiences that align with their values and aspirations, brands can cultivate a sense of connection and belonging, increasing satisfaction and happiness with online purchases. Additionally, experiential marketing enables brands to showcase authenticity and transparency, which today's consumers highly value. Brands that genuinely connect with customers through meaningful experiences are likelier to establish trust and loyalty, resulting in sustained satisfaction and happiness with online interactions (Friedrich, Schlauderer, & Overhage, 2019; Evans, 2019).

Experiential marketing goes beyond standard advertising by delivering immersive experiences that elicit emotions and connect with customers on a human level. These encounters can impact purchasing decisions, long-term brand perceptions, and loyalty. By immersing customers in memorable experiences that align with their values and aspirations, brands can foster a sense of connection and belonging, leading to heightened satisfaction and happiness with online purchases. Moreover, experiential marketing allows brands to demonstrate authenticity and transparency, which today's consumers increasingly value. Brands that authentically engage with customers through meaningful experiences are more likely to build trust and loyalty over time, resulting in sustained satisfaction and happiness with online interactions (Evans, 2019).

In much as Han, Nguyen and Lee (2015) have spoken about experiential marketing and its effects on customer e-satisfaction, they have overlooked this issue in an international context like the British context, Indonesian context, Malaysian context, and the same problem has hardly been communicated about in the South African context especial in South Africa Eastern Cape Province in particularly at Mthatha.

According to Shumba and Ferreira (2023), the broad concept of e-commerce encompasses many facets of experiential marketing and e-business outlets, including consumer e-satisfaction, customer happiness, and the incidence of competitive advantage. The goal of this research is to look at the impact of experiential marketing on customer e-satisfaction and enjoyment with online purchases in Mthatha. Over and above, this study aims to add to the current body of knowledge through practical and intellectual contributions. It is in the researcher's best interests to provide fresh knowledge on the relationship between experiential marketing characteristics, consumer e-satisfaction, and customer happiness, particularly in Mthatha, Eastern Cape, South Africa.

2. Theoretical Grounding

The theoretical grounding section presents the underlying theoretical frameworks that guide this research, namely the Social Exchange Theory (SET) and the Technology Acceptance Model (TAM). SET offers valuable insights

into the exchange dynamics of social interactions and relationships, while TAM provides a robust framework for understanding the acceptance and adoption of technology by individuals. These theories collectively inform the conceptualisation of research problems and the formulation of hypotheses.

2.1 Social Exchange Theory

The Social Exchange Theory was developed by sociologist George C. Homans in the 1950s and further elaborated upon by other theorists such as Peter Blau and Richard Emerson. This study has adopted Social Exchange Theory to explain the nature of customer e-satisfaction and customer happiness in online shopping. Social Exchange Theory argues that attitudes and behaviours are determined by the rewards of interaction minus the penalties. This implies that rewarding customers for a particular positive action leads to customer satisfaction and customer happiness (Kim & Qu, 2020).

According to Nachmias, Mitsakis and Aravopoulou (2022), Social Exchange Theory is a cornerstone in understanding human interactions and relationships, rooted in the premise that individuals engage in social relationships to maximise rewards and minimise costs. At its core, the theory posits that people weigh the benefits and drawbacks of a relationship, and their decisions are guided by the perceived value of the outcomes they receive from it. Central to this theory is the concept of reciprocity—individuals aim to balance what they invest in a relationship and what they gain from it. This exchange occurs within various social contexts, from intimate relationships to professional interactions.

In intimate relationships, social exchange theory suggests that individuals evaluate the rewards and costs associated with their partner's actions. Rewards may include love, companionship, and support, while costs might entail sacrifices, conflicts, or emotional distress. People assess whether the benefits of staying in the relationship outweigh the drawbacks, and they adjust their behaviours accordingly. For instance, someone might invest more effort into a relationship if they perceive their partner's actions as highly rewarding, leading to a more profound commitment (Mirzaei & Esmaeilzadeh, 2021).

Social Exchange Theory is highly relevant to this study because it helps understand customer satisfaction and happiness with online purchases. This theory posits that individuals engage in social interactions based on the principle of maximising rewards and minimising costs. This theory can be applied to the relationship between customers and online retailers in online shopping. Social exchange theory emphasises the importance of trust in relationships. In online shopping, customers rely on trust signals such as positive reviews, brand reputation, secure payment methods, and transparent return policies. When customers trust the online retailer, they are more likely to engage in transactions with them, leading to higher satisfaction and happiness if the transaction meets or exceeds their expectations. Social exchange theory suggests that individuals feel a sense of obligation to reciprocate when they receive benefits from others. In the context of online shopping, this can manifest in various forms such as discounts, loyalty rewards, personalised recommendations, and excellent customer service.

2.2 Technology Acceptance Model Theory

The Technology Acceptance Model was introduced by Fred Davis in 1986. Technological system usability may significantly shape users' behaviour (Chen, Xu, & Arpan, 2017; Förster, 2024).

The Technology Acceptance Model is relevant to this study as it will assist e-business stores with prominent strategies to entice customers' attention and publicity. This study will give marketers and managers insight into the relationship between experiential marketing dimensions and customer e-satisfaction to achieve customer happiness in online purchases. The Technology Acceptance Model (TAM) is a widely used framework for understanding users' acceptance of technology, particularly in the context of information systems and software. It primarily focuses on two key factors: perceived usefulness and perceived ease of use. These factors influence

users' attitudes towards adopting and using a particular technology. When applied to the context of e-commerce and online purchases, TAM provides valuable insights into customers' satisfaction and happiness.

3. Conceptual Model & Hypothesis Development

The model visually depicted the causal relationships between the predictor variables, the mediator variable, and the outcome variable. Hypotheses were formulated based on this conceptual framework to guide the empirical investigation of the relationships between the constructs (see Figure 1).

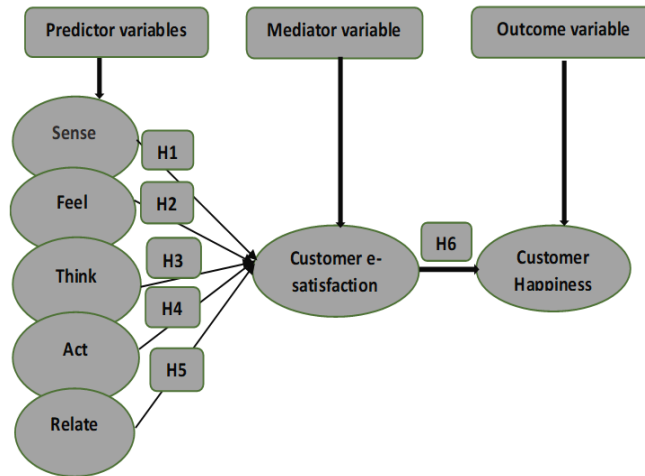


Figure 1. Conceptual model
Source: developed by the authors

3.1 Sense Experience and Customer E-Satisfaction

Sense experience refers to customers' overall sensory perception when interacting with a product, service, or brand. It encompasses sensory inputs such as sight, sound, touch, smell, and taste. When these sensory inputs are strategically designed and integrated into the customer experience, they can significantly impact customer e-satisfaction, or electronic satisfaction, which relates to customers' satisfaction with their online interactions and experiences. Sense experience plays a crucial role in shaping customers' e-satisfaction by enhancing the overall user experience, creating emotional connections, influencing perceptions of quality, and fostering engagement and advocacy. By strategically designing sensory experiences that align with their brand values and target audience preferences, companies can effectively increase customer satisfaction and drive loyalty in the digital realm (Foroudi, Melewar & Jin, 2024). Therefore, the following hypothesis is proposed:

H₁. Sense experience has a negative relationship with customer e-satisfaction.

3.2 Feel Experience and Customer E-Satisfaction

Emotional marketing aims to evoke feelings and moods that align with the company's brand. Positive or negative emotions towards a product or service can significantly impact consumer behaviour. It involves using emotional triggers to influence consumer emotions, ranging from creating a cheerful mood to evoking strong feelings of joy and pride. The most impactful impressions often occur during initial contact with the product and can be reinforced over time. When customers feel appreciated and understood, they are more likely to develop brand loyalty (Kemp, Briggs & Anaza, 2020). Hence, it can be hypothesised that:

H₂. Feel experience has a positive relationship with customer e-satisfaction.

3.3 Think Experience and Customer E-Satisfaction

Thinking is the experience that stimulates customers to be creative in developing a new idea or thinking about a company or its products. Think experiences are integral to customer e-satisfaction in the digital landscape. Businesses can create online environments that foster customer satisfaction and loyalty by prioritising user-friendly interfaces, personalisation, efficiency, effective communication, and consistency (Moodley & Buthelezi, 2023). These efforts not only enhance the overall customer experience but also contribute to long-term success in an increasingly competitive digital market. Hence,

H₃. Think experience has a positive relationship with customer e-satisfaction.

3.4 Act Experience and Customer E-Satisfaction

The act experience, which refers to customer interactions and engagements with a company or brand, plays a significant role in shaping customer satisfaction. Act experiences directly influence customer satisfaction by providing personalised, efficient, consistent, and engaging interactions, resolving issues effectively, fostering emotional connections, and demonstrating a commitment to continuous improvement. By prioritising the Act experience, companies can cultivate positive customer relationships and drive greater satisfaction and loyalty over time. Act experiences are pivotal in shaping customer satisfaction and fostering a positive relationship between consumers and businesses. Central to this relationship is the notion of personalised interactions. When companies tailor their engagements to suit individual customer preferences and needs, it communicates a profound sense of value and understanding. This personal touch goes a long way in cultivating satisfaction as customers feel acknowledged and appreciated in their interactions (Dash, Kiefer & Paul, 2021). Therefore, it can be hypothesised that:

H₄. Act experience has a positive relationship with customer e-satisfaction.

3.5 Relate Experience and Customer E-Satisfaction

Related experience among employees positively correlates with customer satisfaction by improving understanding, problem-solving capabilities, trust, service quality, communication, efficiency, and fostering long-term relationships. Investing in employee training and development to build relevant experience can yield significant returns in terms of customer satisfaction and loyalty. Related experience is pivotal in shaping customer satisfaction, acting as the bedrock upon which fruitful interactions are built. When employees possess relevant experience in their field, they inherently grasp the intricacies of customer needs and preferences (Brito, Félix & Mena, 2023). This understanding empowers them to navigate interactions with finesse, anticipating and addressing customer requirements precisely. Such adeptness fosters a sense of validation for the customer and elevates their overall satisfaction by aligning service delivery closely with their expectations. Hence:

H₅. Relate experience has a positive relationship with customer e-satisfaction.

3.6 Customer E-Satisfaction and Customer Happiness

E-satisfaction is a post-purchase measurement index that measures the state of consumer feelings about past purchases and shopping experiences. The measurement of consumer satisfaction level is risky because satisfaction with distribution services can influence consumers' decision to continue using them (Nisar, & Prabhakar, 2017). According to Schlauderer and Overhage (2019), consumer satisfaction is a response to the accumulation of shopping and consumption experiences made by consumers towards a brand. Customer e-satisfaction and happiness are closely intertwined. A positive online shopping experience, characterised by ease of use, meeting or exceeding expectations, perceived value, convenience, and loyalty, directly contributes to customer happiness. By prioritising these aspects of the online shopping journey, brands can enhance customer satisfaction and contribute to their overall happiness and well-being.

H₆. Customer e-satisfaction has a positive relationship with customer happiness.

4. Methodology

There are various methodologies to choose from, depending on the nature of the study. However, this study is a quantitative study. The research method is a general approach and technique used to conduct a research study on a particular topic of interest (Sovacool, Axsen & Sorrell, 2018). Schaarschmidt and Morgan (2024) suggest that the choice of method varies depending on whether it is qualitative, quantitative, or mixed. This study will employ a positivist paradigm to achieve the objectives. The epistemological approach is likely to be positivist among the three philosophical elements of research: epistemology, axiology, and ontology. According to Mohsin, Ali, and Albayati (2024), positivism is closely associated with the characteristics and logic of the quantitative method. The positivist paradigm is selected because it gives the researcher independence and objectivity. Additionally, positivism allows for an objective analysis of facts and uses existing theories to formulate hypotheses. Moreover, variables can be investigated without the researcher's control or influence.

4.1 Data Collection Tool

The determining factor of the data collection tool that the researcher uses is the variables that this study aims to investigate. Preceded by the study's objectives, a fully structured self-administered questionnaire has been deemed the most suitable data collection tool. Primary data will be collected with the help of three assistants to speed up the process and ensure a positive response rate. The advantage of a questionnaire is that it reduces costs and guarantees anonymity (Al Saied & Alkhoraif, 2024).

4.2 Population and Sampling

According to Yuan et al. (2024), it is affirmed that the population is crucial as it delineates the scope and boundaries of the study. In this research study, the population comprises 3000 customers who engage in online purchases. These individuals are drawn from e-business stores' official websites, such as Facebook. The assumption underlying this population selection is that virtually everyone who purchases online will likely have a social media account, such as Facebook. Social media platforms like Facebook are widely utilised for various purposes, including connecting with brands and businesses, browsing products, and making purchases. Therefore, targeting customers who use online purchase platforms and are active on social media allows the researcher to access a sizable and relevant population for the study. By selecting this population, the researcher aims to capture a representative sample of individuals actively involved in online purchases, thereby ensuring the applicability and generalizability of the study findings to the broader population of online shoppers.

The literature distinguishes between two main types of sampling methods: probability sampling and non-probability sampling. Probability sampling, as defined by Fakih et al. (2023), involves selecting samples from a large population using methods grounded in probability theory. This approach ensures that each member of the population has a known and non-zero chance of being selected for the sample.

In this study, a simple random sampling method was adopted, which falls under the category of probability sampling. In simple random sampling, each member of the population has an equal chance of being selected for the sample. As described, simple random sampling is a probability sampling method where the selection process is independent of any individual characteristics, such as age, gender, employment status, or location. In this study, questionnaires were distributed to available and willing participants at various locations, including King Sabatha Dalindyebo local municipality, Walter Sisulu University Zamukulungisa site & NMD site, and Mthatha. This sampling approach was chosen for its practicality and convenience in accessing participants within the study's context.

4.3 Data Analysis

Accordingly, quantitative data was collected from 300 customers who purchased goods and services online using a questionnaire. Composite reliability was employed to evaluate the measurement scale and confirm the internal consistency and reliability of the instrument used in the study. According to Sovey, Osman and Mohd-Matore (2022) the composite reliability value should be greater than 0.6, then the instruments are reliable. In this study, Smart PLS was used to compute composite reliability, and the results depict that all variables meet the acceptable threshold of 0.6. Hence, all the measurement instruments used in this study are deemed reliable.

Table 1. Reliability test results
Cronbach Alpha and Composite Reliability

	Cronbach's alpha	Composite reliability (rho_a)
Act experience	0.897	0.899
Customer e-satisfaction	0.908	0.909
Customer happiness	0.894	0.898
Feel experience	0.852	0.862
Relate experience	0.869	0.871
Sense experience	0.726	0.808
Think experience	0.839	0.843

Note: SE = Sense Experience; FE = Feel Experience; TE = Think Experience, AE= Act Experience, RE= Relate Experience, CS = Customer E-satisfaction and CH = Customer Happiness. Table 1 presents Cronbach's alpha and composite reliability (rhoa) values for different constructs in a study. Cronbach's alpha and composite reliability are both measures of internal consistency reliability, which assess the extent to which the items within each construct consistently measure the same underlying concept. Across all constructs, both Cronbach's alpha and composite reliability consistently surpass 0.7, indicating robust internal consistency reliability. Specifically, act experience, Customer e-satisfaction, and Customer happiness exhibit high reliability, with Cronbach's alpha values of 0.897, 0.908, and 0.894, respectively, and corresponding composite reliability values of 0.899, 0.909, and 0.898. The sense experience construct shows a slightly lower Cronbach's alpha at 0.726 but maintains a reasonable composite reliability of 0.808. The remaining constructs, feel experience, relate experience, and Think experience, demonstrate reliability ranging from 0.839 to 0.852 for Cronbach's alpha and from 0.862 to 0.871 for composite reliability. Overall, these findings affirm the reliability of the measurement instruments utilised across various constructs in the study, facilitating robust data interpretation and analysis.

Table 2. Validity test results
Average variance extracted

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
AE	0.897	0.899	0.929	0.765
CH	0.894	0.898	0.919	0.654
CS	0.908	0.909	0.927	0.646
FE	0.852	0.862	0.901	0.696
RE	0.869	0.871	0.911	0.719
SE	0.726	0.808	0.844	0.649
TE	0.839	0.843	0.892	0.675

Note: SE = Sense Experience; FE = Feel Experience; TE = Think Experience, AE= Act Experience, RE= Relate Experience, CS = Customer E-satisfaction and CH = Customer Happiness.

The Average Variance Extracted (AVE) values provided indicate the average amount of variance captured by each latent construct in a structural equation model. Typically, AVE values above 0.5 are considered acceptable, indicating that the constructs explain more than 50% of the variance in their respective observed variables and suggesting good convergent validity. In these findings, all the AVE values surpass the threshold, ranging from 0.646 to 0.765, indicating that each latent construct explains a substantial proportion of the variance in its

indicators. This suggests that the measurement model is reliable and that the constructs are adequately represented by their indicators, contributing to the overall validity of the structural equation model.

Table 3. Model fit

	Saturated model	Estimated model
SRMR	0.060	0.065
d_ULS	1.923	2.231
d_G	0.874	0.897
Chi-square	1401.776	1427.739
NFI	0.794	0.790

Table 3 compares the fit indices of a saturated model with those of an estimated model. Fit indices are used to evaluate how well a model fits the observed data. The first row presents the Standardised Root Mean Square Residual (SRMR), which measures the average discrepancy between the observed and model-implied covariance matrices. In the saturated model, the SRMR is 0.060, while in the estimated model, it is slightly higher at 0.065. The second row displays the Normed Fit Index (NFI), which assesses the relative fit of the model compared to a null model. Both models have similar NFI values, with the saturated model at 0.794 and the estimated model at 0.790. Overall, while the fit indices between the two models are quite close, indicating relatively good model fit, slight differences are observed, particularly in the SRMR values, suggesting potential variations in model fit between the saturated and estimated models.

4.4 Structural Model Assessment – Hypotheses Testing

Once the proposed measurement and structural model have been rigorously assessed and refined, the subsequent step involves delving into the causal relationships between latent variables using path analysis. This statistical method allows researchers to scrutinise the connections between variables, both direct and indirect, within a structural equation model framework. The process entails specifying a theoretical model that elucidates the hypothesised relationships among latent variables and their observed indicators. Following data preparation and model estimation, researchers evaluate the model's fit to the data using various indices and statistical tests. Interpreting the results involves discerning the strength and significance of the estimated paths, thereby elucidating the underlying causal mechanisms in the research domain.

According to Rodríguez & Ferreira (2024), SEM assumes that latent variables directly or indirectly influence other latent variables in the model, resulting in estimation results that explain how these latent variables are related. Table 4 below shows the estimated results of hypothesis testing in the present study. Figure 2 summarises the proposed hypotheses, path coefficients, t-statistics, and whether a hypothesis is accepted or rejected. According to the literature, higher path coefficients indicate strong relationships between latent variables and $t > 1.96$, which is a measure of the significance of the relationship (Purwitasari & Purnomo, 2023; da Silva et al., 2024).

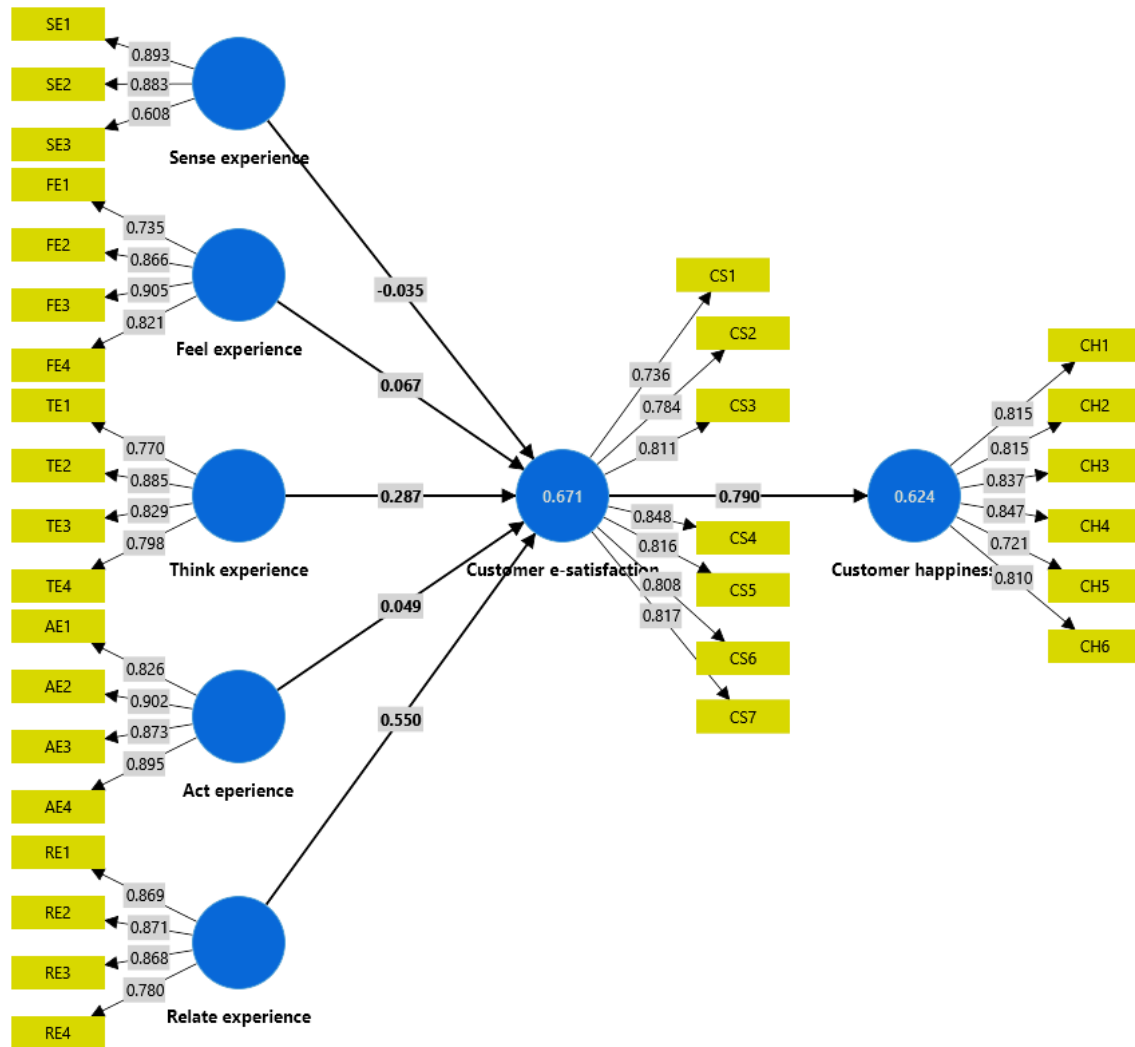


Figure 2. Structural Model

Note: SE = Sense Experience; FE = Feel Experience; TE = Think Experience, AE= Act Experience, RE= Relate Experience, CS = Customer E-satisfaction and CH = Customer Happiness

The individual path coefficients of H1, H2, H3, H4, H5 and H6 were -0.035; 0.067, 0.287, 0.049, 0.55 and 0.79, respectively. These results generally indicate that some hypothetical relationships have a positive association while H1 has a negative association with H5. Notably, the negative association between SE and CS (H1) contrasts with the positive associations observed in other relationships, highlighting the nuanced impact of different factors on customer satisfaction within the structural model. Similarly, to obtain and validate the directed dependencies among the variables, a Path Analysis was conducted as shown in Table 4 below.

Table 4. Path Analysis Results

Hypothesised relationship	Hypotheses	Path Co-efficient	T- statistics	P-value	Outcome
SE → CS	H1	-0.035	0.700	0.484	Insignificant & not supported
FE → CS	H2	0.067	1.008	0.314	Insignificant & not supported
TE → CS	H3	0.287	3.449	0.001	Significant & supported
AE → CS	H4	0.049	0.722	0.47	Insignificant & not supported
RE → CS	H5	0.55	9.049	0.00	Significant & supported
CS → CH	H6	0.790	26.66	0.00	Significant & supported

Note: SE = Sense Experience; FE = Feel Experience; TE = Think Experience, AE= Act Experience, RE= Relate Experience, CS = Customer E-satisfaction and CH = Customer Happiness

This table outlines the hypothesised relationships, path coefficients, t-statistics, p-values, and outcomes for a series of hypotheses tested in a research study. Each row represents a different hypothesis, with the independent variable listed first, followed by the dependent variable (e.g., SE CS represents the relationship between Sense experience and Customer satisfaction). The path coefficients quantify the strength and direction of the relationship between variables. In this analysis, the hypothesis regarding the relationship between Sense experience and Customer satisfaction (H1) shows a path coefficient of -0.035, with a t-statistic of 0.7 and a p-value of 0.484, indicating an insignificant and unsupported relationship. Similarly, the hypotheses concerning Feel experience (H2) and Act experience (H4) also yield insignificant and unsupported results. However, hypotheses related to Think experience (H3), Relate experience (H5), and Customer satisfaction leading to Customer happiness (H6) exhibit significant and supported relationships, as evidenced by their respective path coefficients, t-statistics, and p-values. For instance, H5 shows a strong path coefficient of 0.55, with a high t-statistic of 9.049 and a very low p-value of 0.00, indicating a significant and supported relationship between Relate experience and Customer satisfaction.

4. Results

Results after H₁ test

The results obtained after the H1 test confirmed a correlation between data sense experience and the customer's e-satisfaction with online service. After testing H1, a course coefficient of -0.035 was obtained. This indicates that sense experience (SE) has a negative influence on Customer E-satisfaction (CS). Furthermore, the results show that the relationship between sense experience is nonsignificant and positively correlated ($t=0.7$, $p=0.484$). The study revealed a negative association between sense experience and customer e-satisfaction in the context of online purchases. This indicates that as sense experience increases, customer e-satisfaction with online purchases tends to decrease. In other words, a greater emphasis on sense experiences, such as sensory aspects of products or the shopping environment, is associated with lower customer satisfaction with their online shopping experience.

Results after H₂ test

The results obtained after testing H₂ confirmed that there is a relationship between feel and customer e-satisfaction. After testing H₂, a course coefficient of 0.067 was obtained. This indicates that feeling experience positively influences customer e-satisfaction (CS). Furthermore, the results show that the feeling experience is significantly positively correlated ($t=1.008$, $p=0.314$). This means that the observed correlation between the variables is not likely due to random chance, providing evidence for a genuine relationship. These findings highlighted the importance of providing customers with a positive Feel Experience when using online services, which can significantly contribute to their overall satisfaction. It may be beneficial for service providers to focus on enhancing the emotional and affective aspects of their online services.

Results after H₃ test

The results obtained after testing H₃ confirmed the relationship between think experience and customer e-satisfaction. After testing H₃, a path coefficient of 0.287 was obtained. This indicates that think experience (TE) positively impacts customer e-satisfaction (CS). Moreover, the results show that the relationship between website design is significantly positively correlated ($t = 3.449$, $p = 0.001$).

Results after H₄ test

The results obtained after the H₄ test confirmed a correlation between the act experience and customer e-satisfaction. After testing H₄, a path coefficient of 0.049 was obtained. This indicates that the act experience positively impacts customer e-satisfaction (CS). Moreover, the results show that the relationship between the overall quality of online services is significantly positively correlated ($t=0.722$, $p=0.47$).

Results after H₅ test

The results obtained after the H₅ test confirmed a correlation between the related experience and customer e-satisfaction. After testing H₅, a path coefficient of 0.55 was obtained. This indicates that the relate experience positively impacts customer e-satisfaction (CS). Moreover, the results show that the relate experience relationship is significantly positively correlated ($t = 9.049$, $p = 0.000$).

Results after H₆ test

The results obtained after the H₆ test confirmed a correlation between customer e-satisfaction and customer happiness. After testing H₆, a path coefficient of 0.0.79 was obtained. This indicates that customer e-satisfaction positively impacts customer happiness (CH). Moreover, the results show that the related experience relationship is significantly positively correlated ($t = 26.66$, $p = 0.000$).

Conclusions

The findings of this study present a nuanced understanding of how different dimensions of customer experience—sense, feel, think, act, and relate—impact e-satisfaction in online environments, and how this satisfaction ultimately drives customer happiness. Notably, sense experience (H₁) demonstrated a negative and statistically nonsignificant influence on e-satisfaction (coefficient = -0.035 , $p = 0.484$). This suggests that trying to recreate sensory elements in a digital context—such as visuals, audio, or simulated tactile features—may not effectively contribute to customer satisfaction and may even have a counterproductive effect. The online medium inherently lacks physical interaction; therefore, sensory experience alone is not a reliable driver of satisfaction in e-commerce.

In contrast, the feel (H₂), think (H₃), act (H₄), and relate (H₅) experiences all had positive impacts on customer e-satisfaction, with the relate and think dimensions emerging as particularly influential. The relate experience, which involves fostering personal identity, connection, and social belonging, exhibited the strongest positive correlation (coefficient = 0.55 , $p = 0.000$), suggesting that customers highly value online experiences that help

them feel connected to others or reflect their values. Similarly, the think experience (coefficient = 0.287, $p = 0.001$) highlights the importance of intellectually engaging content—such as innovative design or problem-solving features—in enhancing satisfaction. Although the feel and act experiences were positively related to e-satisfaction, their influence was weaker and statistically nonsignificant, indicating that emotional and behavioural engagement still matter but may not be as critical in isolation.

Most importantly, the final hypothesis (H6) revealed a strong and statistically significant relationship between customer e-satisfaction and customer happiness (coefficient = 0.79, $p = 0.000$). This affirms that improving customer satisfaction enhances transactional success and contributes to the customer's broader emotional state and long-term loyalty. When customers are satisfied with their online shopping experiences—particularly through cognitive stimulation and meaningful connections—they are more likely to feel happier overall. This reinforces the strategic value of focusing on customer experience design not just as a tool for sales conversion, but as a foundational component of long-term brand affinity and emotional engagement.

Therefore, businesses must address consumer concerns and build trust, particularly for those who may be hesitant about online purchases. This can be achieved by ensuring strong security protocols, offering clear and straightforward return policies, and creating user-friendly websites. Including customer reviews, ratings, and other forms of social proof can also alleviate potential doubts and contribute to a more favourable brand image. As customer happiness is deeply tied to the sense of trust and value they experience during the purchase process, businesses must make their online platforms visually appealing but also secure, functional, and transparent.

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Author Contributions: the authors contributed equally. All authors have read and agreed to the published version of the manuscript.

Lucas VUKETHWELE, Mr.

ORCID ID: <https://orcid.org/0009-0000-3879-0181>

Siphenathi FIHLA, Dr.

ORCID ID: <https://orcid.org/0000-0001-9632-2650>

Richard CHINOMONA, Prof.

ORCID ID: <https://orcid.org/0000-0002-6967-0390>

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OPTIMIZATION OF BUILDING AIR CONDITIONING USING A HYBRID COGENERATION SYSTEM WITH PHOTOVOLTAIC ENERGY*

Salma Sebbaghi ^{1*}, Zineb Aqachmar ², Najiba El Amrani ³, Manuela Tvaronavičienė ⁴

^{1*,3} Sidi Mohamed Ben Abdellah University, faculty of science and techniques Fez, USMBA, Morocco

² Cadi Ayyad University, Marrakech UCA, Morocco

² University of Quebec in Abitibi-Témiscamingue UQAT, Canada

⁴ Vilnius Gediminas Technical University, Vilnius, Lithuania

*E-mails: ¹salma.sebbaghi@usmba.ac.ma (Corresponding author); ²zineb.aqachmar@uca.ac.ma; ³najiba.elamrani@usmba.ac.ma; ⁴manuela.tvaronavičienė@vilniustech.lt

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Abstract. Photovoltaic (PV) systems are a promising alternative for electricity production as they harness solar energy, a clean and renewable source, reducing reliance on fossil fuels and minimizing environmental impact. However, the overall efficiency of conventional PV systems remains limited since a significant portion of the incident solar energy is converted into heat, which is typically wasted (Zhou et al. 2025). To address this issue, in this paper we are developing a cogeneration system (PV/T) that not only generates electricity but also captures and utilizes the excess thermal energy for space heating (Wei et al. 2025). This system integrates a heat storage solution to enhance energy availability and optimize thermal management, ensuring improved overall efficiency and better utilization of solar resources. To achieve this, we will use Matlab/Simulink to design and simulate a Photovoltaic Thermal (PV/T) Hybrid Solar Panel system, allowing us to analyze its performance and optimize its operation for residential heating applications. As results, we will obtain key parameters such as module temperature, electrical power output, and the required storage tank volume. Additionally, we will test different PV technologies, comparing their performance to identify the most suitable option for the climatic conditions of Lithuania. Furthermore, we will observe solar variables variations and pump flow rates to assess their impact on system efficiency and optimize energy distribution. These results highlight the potential of PV/T technology for optimizing solar energy utilization in residential heating. Further experimental validation is needed to refine the model and optimize system performance for different climatic conditions.

Keywords: Photovoltaic Thermal (PV/T) Hybrid Solar Panel; solar variables variations; pump flow

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1. Introduction

As climate concerns grow and energy prices rise, solar energy has become a vital alternative for residential energy systems (Castillo-Díaz et al., 2024; Pizzuti et al., 2024; Firoozi et al., 2025; Spellmeier et al., 2025).

Photovoltaic (PV) technology, in particular, allows clean electricity generation directly from sunlight. However, traditional PV panels typically convert only 15–20% of solar radiation into electricity, with the rest lost as heat, reducing efficiency and increasing cell temperature, which can further degrade performance (Kalogirou, 2004; Kuang & Wang, 2006). This thermal waste not only reduces electrical performance but misses an opportunity to recover energy that could otherwise support domestic heating needs especially in countries with cold climates.

To address this, hybrid photovoltaic/thermal (PV/T) systems have been developed, which integrate solar cells and thermal collectors in a single unit to simultaneously generate electricity and useful heat (Chow, 2010; Obalanlege et al., 2020). These systems have demonstrated high efficiency and flexibility, making them attractive for residential cogeneration applications. For example, a study conducted in northwestern China investigated the performance of a micro heat pipe PV/T system inside a greenhouse and showed total efficiencies of 53.6%, 52.0%, and 42.9% on sunny, partly cloudy, and overcast days respectively. These results represented 14.7% to 21.3% performance gains over identical systems installed outdoors, confirming the importance of environmental control and tilt optimization (Zhou et al., 2025).

Cost-effective PV/T designs have been proposed to reduce material use and manufacturing complexity, such as plateless absorbers and polymer-based exchangers (Zondag et al. 2002). Wei et al. (2025) proposed a low-cost absorber-plateless PV/T design using plastic capillary mats as heat exchangers. Despite the absence of a traditional metal absorber plate, the system achieved thermal efficiencies ranging from 26.4% to 33.4%, and overall efficiencies above 50%. Furthermore, the levelized cost of heat was reduced significantly, falling between 0.010 and 0.013 USD/kWh much lower than that of conventional PV/T systems with metal components. These innovations suggest that PV/T technology can be scaled to building applications without prohibitive cost.

Material and structural innovations have also contributed to performance gains. A flat-plate PV/T system using CdTe thin-film solar cells showed higher electrical performance under elevated temperatures than polycrystalline silicon modules, thanks to the lower temperature sensitivity of CdTe cells (Li et al., 2021). The sandwich structure of the panel also helped resist environmental degradation. In their experimental and numerical study, Wang et al. found that increasing the cell coverage ratio improved overall system performance, and reducing the air gap thickness between layers enhanced heat transfer. These findings underscore the value of component-level optimization in adapting PV/T systems to specific climates.

Further advancement came from low-concentration PV/T designs. Zhang et al. (2019) compared a low-concentration PV/T system (LCPV/T) with a flat-plate PV/T module. They found that the LCPV/T system produced three times more electrical power and nearly double the thermal output, albeit with some trade-offs in heat transfer stability. While more complex to build, these systems point to the potential of enhancing solar capture without significantly expanding panel surface area an important consideration in urban settings.

In addition to physical configuration, operational strategies are increasingly recognized as key factors in improving PV/T system performance within building energy networks. Recent studies have evaluated strategies such as maximum self-consumption (MSC), time-of-use (TOU), and optimization-based control (OPT), finding that each approach offers different trade-offs in efficiency, cost, and grid interaction. For instance, the OPT strategy offered the greatest flexibility and lowest operational cost, though with reduced energy utilization efficiency and a greater impact on the grid. In contrast, the MSC strategy showed low sensitivity to battery charge states and exhibited more stable performance. Battery and thermal storage sizing were also affected, with optimal

capacities for different strategies ranging from 2.5 to 4.5 kWh and 100 to 200 L (Wang et al., 2024). These insights are especially important in designing PV/T systems for seasonal climates, where thermal demand and solar availability vary widely across the year.

This operational perspective is particularly relevant for Lithuania, where cold winters dominate the energy demand profile, and residential heating is one of the most significant energy uses. Despite moderate annual solar irradiance, Lithuania's seasonal thermal needs align well with the dual-output capacity of PV/T systems, particularly when integrated with intelligent storage and control strategies. However, there remains a lack of tailored system modelling that accounts for Lithuanian climate specifics and residential consumption behaviour.

This study addresses that gap by developing and simulating a PV/T hybrid cogeneration system for space heating in Lithuanian homes. Using MATLAB/Simulink, we will analyse key parameters such as electrical and thermal output, module temperature, storage sizing, and system responsiveness to solar variation. We will also compare different PV technologies to determine which offers optimal performance under local conditions. Ultimately, this work aims to support the design of smarter, more efficient solar energy systems that are both technically and economically viable in northern European climates

2. Systeme description

2.1. Mathematic model

The hybrid photovoltaic/thermal (PV/T) system modeled in this study is a flat-plate solar collector designed to simultaneously produce electricity and low-temperature thermal energy.(El Ouakili et al. 2024) It comprises multiple thermally and optically interactive layers: a transparent glass cover, a photovoltaic (PV) cell layer, an absorber plate with thermal contact to embedded fluid-carrying tubes, and a water circulation loop for heat extraction. The modeling approach follows the methodology of (da Silva & Fernandes 2010) and other PV/T modeling efforts using dynamic simulation and energy balance techniques (Hegazy, 2000; Sami, 2019), where each physical layer is described by a transient one-dimensional energy balance, ensuring spatial and temporal resolution of heat accumulation and transfer phenomena across the collector components.

The optical behavior of the system is governed by the combined transmittance and absorptance properties of the glass and PV surface. Solar irradiance G_{GG} enters the collector and is partially reflected and absorbed. (Farkad et al. 2024)The effective solar input G_{eff} reaching the PV cell is modeled using:

$$G_{eff} = G \cdot \tau \cdot \alpha \quad (1)$$

where τ is the transmittance of the glass and α the effective absorptance of the PV surface.

This energy is split between electrical and thermal pathways. The electrical conversion efficiency η_e of the PV cell is temperature-dependent and follows:

$$\eta_e = \eta_{ref} [1 - \beta(T_{pv} - T_{ref})] \quad (1)$$

where β is the thermal degradation coefficient, and T_{pv} is the temperature of the PV cell. The electrical power output is thus:

$$P_{elec} = \eta_e \cdot G_{eff} \cdot A \quad (1)$$

The residual portion of the solar energy not converted into electricity is dissipated as heat and distributed across the layers of the system. Each solid component in the system is modeled as a lumped thermal mass, governed by a first-order energy balance equation. The glass cover, denoted as layer 1, obeys:

$$m_1 C_{p1} \frac{dT_1}{dt} = h_{conv,1}(T_{amb} - T_1) + \sigma \varepsilon_1 A (T_{sky}^4 - T_1^4) + h_{cond,1}(T_2 - T_1) \quad (1)$$

where T_1 is the glass temperature, $h_{conv,1}$ is the convective heat transfer coefficient with ambient air, and the radiative loss is modeled with the Stefan–Boltzmann law.

The PV layer (layer 2) receives optical input and dissipates waste heat:

$$m_2 C_{p2} \frac{dT_2}{dt} = G_{eff} A (1 - \eta_e) + h_{conv,1}(T_1 - T_2) + h_{cond,2}(T_2 - T_3) \quad (1)$$

The absorber plate (layer 3), thermally connected to the fluid tube, satisfies:

$$m_3 C_{p3} \frac{dT_3}{dt} = h_{conv,2}(T_2 - T_3) + h_{cond,fluid}(T_3 - T_4) \quad (1)$$

The fluid–tube interface (layer 4) is described by:

$$m_4 C_{p4} \frac{dT_4}{dt} = h_{cond,fluid}(T_3 - T_4) - \dot{m} C_p (T_4 - T_{fluid}) \quad (1)$$

Lastly, the working fluid itself, modeled at the average temperature T_{fluid} , exchanges energy with the absorber and flows into a storage tank:

$$m_5 C_{p5} \frac{dT_5}{dt} = \dot{m} C_p (T_4 - T_5) - UA(T_5 - T_{amb}) \quad (1)$$

These coupled equations describe the unsteady heat transfer and energy transformation throughout the collector. Each component's temperature is influenced by solar flux, convective and radiative losses, and thermal interactions with neighboring layers (Aqachmar et al., 2022). The fluid loop completes the cogeneration cycle by recovering heat for domestic hot water or space heating applications.

The described model is highly suitable for simulation in environments like MATLAB/Simulink, where each energy balance equation can be translated into physical blocks representing thermal masses and heat fluxes. It also offers a solid foundation for coupling with electrical and control subsystems, enabling detailed performance evaluation of hybrid PV/T collectors under various climatic conditions, including those representatives of northern Europe such as Lithuania.

2.2. Simulation

The simulation of the hybrid photovoltaic/thermal (PV/T) system was developed in MATLAB/Simulink as in prior numerical simulations of PV/T systems (Villalva, Gazoli & Filho, 2009), using the Hybrid Solar Panel model from MathWorks, built within the Simscape Fluids environment (Figure 2). The model couples electrical, thermal, and hydraulic subsystems to simulate the real-time interaction between solar energy input and the physical structure of a PV/T collector (Ji et al., 2008).

The system consists of a photovoltaic layer with temperature-dependent electrical behavior, a metallic absorber plate in thermal contact with circulating fluid, a transparent cover for optical transmission and thermal insulation, a dynamic water loop with a controlled pump, and a thermal storage tank. In this study, we implemented a glazed,

flat-plate, water-based PV/T collector (Figure 1), which represents the most common configuration for building-integrated applications as supported in the classification of PV/T system architectures (Chow, 2003). This choice is supported by the review of (Cuenca, Ortiz, and Boza 2010), who classify PV/T systems into multiple types: air-based vs. liquid-based collectors, glazed vs. unglazed surfaces, and concentrating vs. non-concentrating designs. While air-based systems offer simpler construction, they suffer from low heat transfer rates and limited thermal efficiency (Jouhara et al. 2016; Yerdesh et al. 2020). Concentrating PV/T collectors can achieve higher temperatures, but require direct solar tracking and are more suitable for large-scale or industrial installations. In contrast, flat-plate water-based collectors, especially with a glazed cover, provide an excellent balance of electrical and thermal performance, compactness, and ease of integration into residential buildings. The use of water as a working fluid enables efficient heat extraction due to its superior thermal properties compared to air, while the glazed cover reduces convective heat losses from the absorber surface, particularly in cold climates.

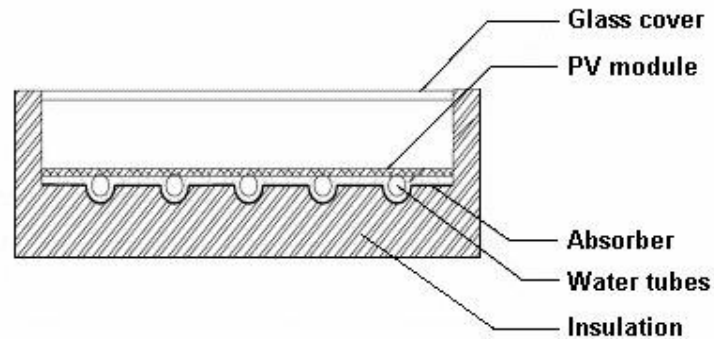


Figure 1. Flat plate PV/T collector
Source: (Ramos, Cardoso & Alcaso 2010)

To simulate the system under realistic conditions, we adapted the model for the local climate of Vilnius, Lithuania, using hourly solar radiation and temperature data from the PVGIS (Photovoltaic Geographical Information System) platform. These meteorological variables were dynamically applied in the simulation as time-dependent inputs. The solar irradiance signal was corrected by cosine projection to represent the effective area seen by the sun, allowing precise calculation of both thermal and electrical outputs. The simulation was carried out over a representative sunny day, selected to analyze system performance under high solar availability. This configuration and approach allow the assessment of the PV/T system's potential for residential energy cogeneration in northern European climates, where both electricity and low-temperature heat are in high demand during the heating season.

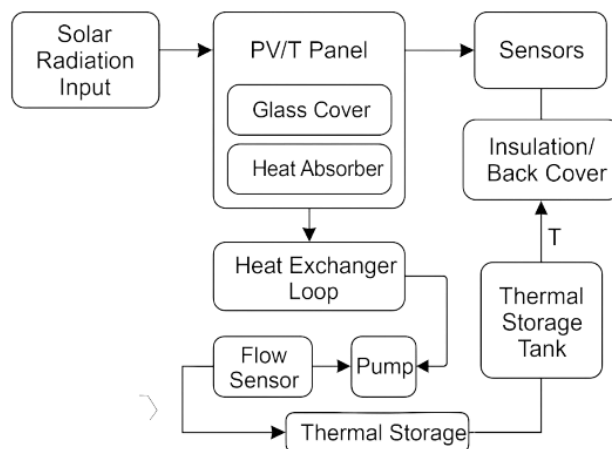


Figure 2. schematic representation of the hybrid PV/T system

To evaluate the impact of photovoltaic technology on the overall performance of the hybrid PV/T system, two different types of solar modules were considered in the simulation: monocrystalline silicon and polycrystalline silicon. These technologies were selected due to their widespread use in commercial applications and their distinct electrical and thermal characteristics. Monocrystalline panels are generally known for their higher efficiency and better performance under low irradiance conditions, whereas polycrystalline panels are more cost-effective and exhibit slightly lower efficiency, particularly at higher temperatures. By simulating both technologies under identical operating conditions, including identical irradiance profiles, ambient temperature, and system configuration, the study aims to highlight how the choice of PV material influences thermal output, electrical production, and overall system efficiency.

The detailed input parameters including nominal power, efficiency at standard test conditions, and surface area, are presented in Table 1.

Table 1. The detail parameter of the PV/T used

Parameters	Values
Pannel	- Canadian Solar CS 3W-453MS (Monocrystalline)
	- Canadian Solar CS 3W-420P (Polycrystalline)
Pipe	
Length	5 m
Section	0.0007 m ²
Hydraulic diameter	0.03 m
Internal roughness	15e-6 m
Tank	
Volume	0.25 m ³
Cross section	0.3 m ²
Pompe	
Internal circuit mass flow	0.02 g/s

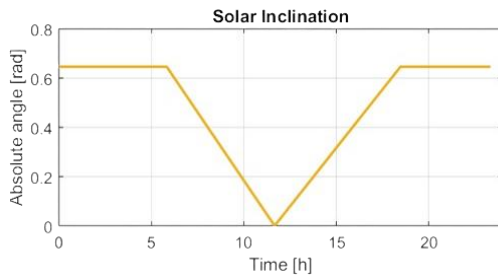
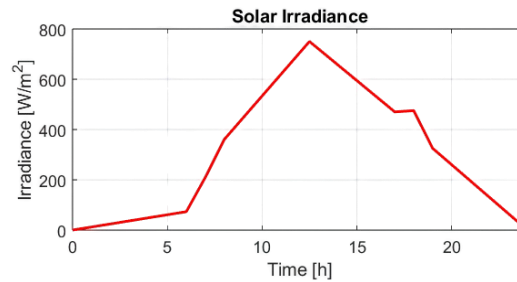


Figure 3. a) optimal inclination for Vilnius



b) radiation for one day in Vilnius

Figure 3 above represent the optimal inclination for Vilnius and the radiation during day in summer.

3. Results and discussion

The simulation results in Figure 4 below offer a clear comparative insight into the performance of a hybrid PV/T system using monocrystalline and polycrystalline photovoltaic technologies. The temperature profiles for both configurations show similar thermal behavior in the glass cover, solar cells, heat exchanger, and storage tank, reflecting that the thermal subsystem's operation is not significantly affected by the PV cell material. However, the **useful electrical power output** consistently shows higher peaks for the monocrystalline panel, with average

electrical energy supplied per day reaching **2.56 kWh/day**, compared to **2.34 kWh/day** for the polycrystalline panel, performance gap between mono- and polycrystalline panels is well documented in the literature (V and M 2018). This higher electrical yield results directly from the intrinsic material properties of monocrystalline silicon, which has fewer grain boundaries, higher carrier mobility, and thus greater conversion efficiency under the same solar irradiation.

The calculated **electrical efficiency** reinforces this difference: **20.5 %** for monocrystalline versus **18.8 %** for polycrystalline. This confirms that monocrystalline panels are more effective at converting solar energy into electricity. Interestingly, the **thermal efficiency** remains almost unchanged between the two technologies, with both systems achieving around **19 %**. This stability arises because the heat extraction process depends mainly on the collector design and heat exchanger effectiveness, rather than the type of PV cell. This is consistent with findings on how absorber structure, glazing, and flow rates dominate thermal behavior (Royne, Dey, and Mills 2005)

The **total system efficiency** combines both contributions and slightly favors the monocrystalline panel (**39.8 %**) compared to the polycrystalline (**37.8 %**). While the difference is modest, it demonstrates the cumulative advantage of higher electrical efficiency over time. The water volume dynamics in the tank also follow similar cycles for both cases, indicating that the thermal energy demand and supply are balanced similarly, independent of the PV module type.

From a practical perspective, these results underline the trade-off between performance and cost. This reflects common challenges in PV/T selection, where monocrystalline panels offer better efficiency, but at higher upfront investment (Hossain et al. 2021). Monocrystalline panels are known for their higher cost per watt due to more complex manufacturing, but they deliver better electrical performance, which can be critical for applications with limited roof area or higher electricity demand. Polycrystalline panels, on the other hand, remain competitive where lower upfront costs are prioritized, and the thermal fraction of the system provides substantial energy savings.

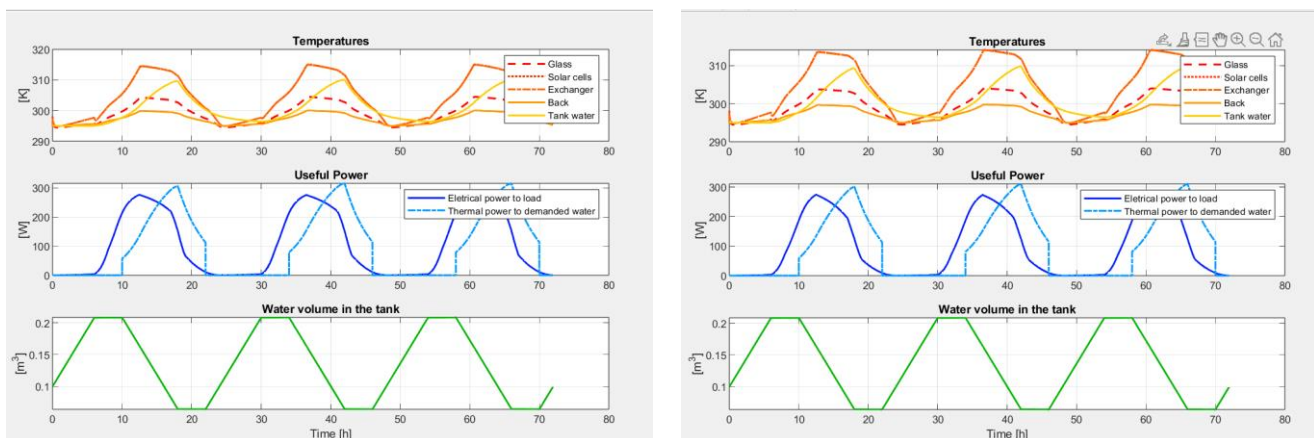


Figure 4. a) The outputs of the model Monocrystalline

b) The outputs of the model Polycrystalline

In summary, the comparative simulation suggests that while both PV/T configurations efficiently combine electrical and thermal production, the **monocrystalline system offers slightly superior overall performance**, especially for electricity-focused applications. However, the small margin in total efficiency should be balanced

with economic factors and local climate conditions when selecting the optimal PV technology for integrated PV/T systems.

Conclusions

This study demonstrated the potential of a flat-plate hybrid PV/T cogeneration system for residential space heating in a cold climate, using detailed MATLAB/Simulink modeling under realistic meteorological conditions for Vilnius, Lithuania. By integrating thermal and electrical outputs, the system effectively recovers a larger portion of incident solar energy than conventional PV modules alone (Tonui & Tripanagnostopoulos 2007). The comparison between monocrystalline and polycrystalline PV panels under identical conditions confirmed that monocrystalline technology achieves slightly higher electrical efficiency (20.5 % vs. 18.8 %) and thus a higher total system efficiency (39.8 % vs. 37.8 %)(Carr and Pryor 2004). However, the thermal efficiency remained practically unchanged for both technologies (~19 %), highlighting that the heat recovery performance depends mainly on the collector design rather than the PV cell type.

These results emphasize that while monocrystalline PV/T systems offer marginally better overall energy yield, polycrystalline systems remain a viable and cost-effective alternative, especially when capital cost constraints are critical (Breyer et al., 2017). For climates like Lithuania's, where heating demand is significant during winter, PV/T technology shows strong potential to reduce reliance on conventional heating sources by utilizing otherwise wasted thermal energy(Sommerfeldt and Madani 2019).

Integrating PV/T systems with seasonal thermal energy storage and novel power-to-X solutions can support year-round renewable heating, with promising techno-economic potential specially in Lithuania because of the cold climates (Baeuerle, Arpagaus & Haller 2025).

Future work should include experimental validation of the model (Bachseitz et al., 2024) (Cao et al., 2025), economic analysis of the lifecycle costs for each PV technology, and an assessment of advanced control strategies to optimize energy management and storage under variable operating conditions.

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Author Contributions: Conceptualization: *Salma Sebbaghi*; methodology: *Salma Sebbaghi, Zineb Aqachmar*; data analysis: *Salma Sebbaghi, Zineb Aqachmar*; writing—original draft preparation: *Salma Sebbaghi*, writing; review and editing: *Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronavičienė*; visualization: *Salma Sebbaghi*. All authors have read and agreed to the published version of the manuscript.

Salma SEBBAGHI is a PhD student at Sidi Mohamed Ben Abdellah University, faculty of science and techniques Fez. Research interests: Electronic Engineering. Renewable energy,

ORCID ID: <https://orcid.org/0009-0003-5133-1969>

Zineb AQACHMAR is the Professor Cadi Ayyad University, Marrakech UCA Morocco and University of Quebec in Abitibi-Témiscamingue UQAT Canada. Research interests: in the field of renewable energy, with a particular focus on solar energy technologies

ORCID ID: <https://orcid.org/0000-0003-4412-5596>

Najiba El Amrani EL IDRISSE is the Professor at Sidi Mohamed Ben Abdellah University, faculty of science and techniques Fez. Research interests: Electronic Engineering. Communication Engineering. Telecommunications Engineering

ORCID ID: <https://orcid.org/0000-0001-5603-1306>

Manuela TVARONAVIČIENĖ is the Professor of economics, Vilnius Gediminas Technical University. Research interests: in the field of economic growth, investments, innovations, sustainable development, sector development

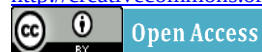
ORCID ID: <https://orcid.org/0000-0002-9667-3730>

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PROTEST ACTION IN THE URBAN PERIPHERIES: ASSESSING RECONCILIATION BETWEEN THE COMMUNITY AND ELITES AFTER THE PROTEST

Sandile Blessing Mkhwanazi ¹, Mandisi Matyana ^{2*}

¹ North-West University, School of Government Studies, Private Bag X6001, Potchefstroom, 2520, South Africa

^{2*} University of Zululand, Department of Public Administration, Private Bag X1001, KwaDlangezwa, 3886, South Africa

E-mails: ¹Blessingsandile2000@gmail.com; ^{2*}matyanam@unizulu.ac.za (Corresponding author)

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Abstract. Urban peripheries in South Africa, especially in metropolitan spaces, have been sites of contestation of power between local government and the communities, and historically they have been sites of resistance against the apartheid government. Violence has always characterised South Africa, and state-sponsored violence has been used as an instrument to curb violence and resistance. Ironically, state-sponsored violence has consistently failed to curb violence and has always resulted in violence. The history of South Africa is further characterised by protest, especially during the apartheid era, as Black Africans protested against the apartheid government that they deemed illegitimate. The ushering of the democratic era promised a new South Africa in which protest action was to be a thing of the past, and in the first decade of democracy, there was little protest action. However, since 2004, protest action emerged and escalated; it has been observed that the protest action is aimed at local government and concentrated at the peripheries (townships and informal settlements). The response by the government has been the use of state-sponsored violence to deal with the increasingly disruptive protests. Employing the qualitative approach, using documentary analysis, this paper seeks to assess the protests at the peripheries and investigate if there are measures to reconcile the community, the local government and the police after the protest action. This paper finds that there are no measures to ensure that reconciliation takes place. Further, there is no understanding of what works regarding reconciliation. Reconciliation is a complex phenomenon, as it means different things to different people and communities, as people are affected by violence in various ways. Further, reconciliation in South Africa is complicated by its violent history; hence, it has become a complex and lengthy.

Keywords: protests; violence; reconciliation; peripheries

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1. Introduction

In the 21st century, service delivery remains vital for every individual and community. It assists citizens in overcoming non-monetary poverty by ensuring they access basic and important municipal services (Matyana & Thusi, 2023; Mamokhere, 2025). According to these scholars, where government services are provided, the community tends to be happy as their living conditions are being taken care of. This assertion is also supported by Waithaka et al. (2020), who state that poor service delivery to communities gives rise to violent protests, which vandalise state resources and other vital infrastructure. These scholars further assert that the cause of violent protests in local communities could be caused by various reasons from the municipal side, such as "infrastructural and resource challenges, weak institutional arrangements, underdeveloped organisational ethics codes, and unaffordable alternative options". These challenges are also supported by scholars such as Thusi et al. (2023), who stated that the causes of poor service delivery in South Africa include a lack of political will, corruption, a

lack of consequence management, the appointment of incompetent staff, etc. Moloto et al. (2020) observed that most South African communities, predominantly rural and urban peripheries, live under severe conditions of poor service delivery; therefore, the government must work very hard to improve the situation. Mamokhere (2020) indicates that such poor service delivery challenges result in protests, which trigger the attention of the media and require the intervention of the police service to make the situation better; however, it must be noted that the solutions to these protests are not the intervention of the police service, but rather the improvement in service delivery.

Community protests in South Africa rose in the apartheid era. During this period, many South African citizens, especially youth, were protesting against unjust treatment and policies by the apartheid government (Moodley & Adam, 2000). During this era, citizens used community protests to express their dissatisfaction with apartheid laws and policies. This protest culture among communities went on after 1994. Citizens were/are still protesting government injustices, especially poor service delivery. Such protests take place in all spheres of government, but local government seem to be the most affected sphere of community protests due to poor service delivery (Dube et al. 2021; Tsheola et al., 2023). These community service delivery protests have occurred in South Africa since 1994. In support, Mamokhere (2020, 2023) states that service delivery protests have increased in South Africa since the freedom era.

Given the above brief view of the importance of service delivery and overview of community protests, this study assesses reconciliation between the community and elites after the protest, particularly within urban peripheries. This is important because the protests mean violence and dissatisfaction among the community members. In this regard, elites are defined as municipal officials who make slow and poor decisions that result in protests and authorise the police to use painful things such as teargas to disperse the protest members. The aim is to check whether the municipal elites engage with community members after the protests, humbly listen to current and future complaints, and make necessary peace. This aim is also supported by scholars such as Matyana and Mthethwa (2024), Yulistiar and Kriswibowo (2024), as municipalities must promote customer care relationships with their clients and treat them with care. This also implies that applying Batho Pele principles encourages public institutions to redress the communities whenever they have done something wrong.

2. Protest and the peripheries

Before defining urban peripheries, the reader needs to understand what a periphery is, in a general sense. A periphery is defined as the external boundaries of something as opposed to its interior or centre. Phelps et al. (2023: 01) define a periphery as "the external boundary of any surface or area or the outer edge of an area". These definitions of "peripheries" also apply to human settlements or communities. In other words, within our societies, some communities are regarded as peripheries, particularly, "urban peripheries". These are places found outside the main cities or towns. They surround the towns; in most cases, they are regarded as townships. Urban peripheries were areas on the outskirts of cities, where people were moving from rural to urban areas, had restricted economies, and had cheaper land prices, density, and access to jobs than more central areas (Meth et al. 2021:03). As newer peripheries formed and older ones were absorbed into the metropolis, this was frequently seen as a shifting edge. The notion of peri-urban areas is pertinent to African cities where there is a blurring of the lines between urban and rural areas, and where fragmented lateral development (Pugh & Dubois, 2021) or the absorption of densifying rural populations (Sawyer et al., 2021) are important aspects of urban growth. However, although these were frequently depicted in older literature as areas of poverty, more recent research shows that middle-class employment and house building have expanded (Bartels, 2020; Mercer, 2020).

3. Research methods

To achieve the research question of this chapter, which is to understand the application of ethics in local government, the chapter used a semi-systematic review, also known as a narrative review approach. A systematic review is an academic synthesis of the available data on a topic that has been presented clearly, utilising critical approaches to locate, characterise, and evaluate relevant research. A systematic review gathers, examines, and evaluates published research data before condensing interpretations into a well-informed conclusion supported by solid evidence (Omazic & Zunk, 2021). In support, Zunder (2021) states that this system incorporates instructions for structuring a written discussion of literature that can be applied to the research process.

Between May 2024 and July 2024, five electronic databases, EBSCOhost, Google Scholar, Sabinet, SAGE journals, and Social Science Citation Index (Web of Science), were examined. The results are shown in Table 1 below. Researchers used the following keywords: “ethics” AND “local government” AND “service delivery”; period 2019-2024.

Table 1. Results of the preliminary literature search using databases.

Databases	Total number of results	Peer-reviewed papers	Included for review
Google Scholar	205	99	17
Sabinet	318	146	11
EBSCOhost	116	13	4
SAGE journals	21	9	2
Social Science Citations Index (Web of Science)	88	14	2

Source: Authors' own compilation

As shown in Table 1, our researcher received 748 articles from the different databases, then the filtering was done to remove articles that are not too relevant to the chapter's aim and protest urban peripheries, leaving a total of 281 relevant articles. After further consideration of the literature and the remaining articles, only 36 were selected to be reviewed.

4. Findings

4.1 Accessibility of the elites

In assessing reconciliation between the community and elites, establishing the connectedness between the community and the elites is necessary before protest activity. Accessibility of the elites is not linear, as local elites are more accessible than provincial or national elites (Kertzer & Renshon, 2022). However, despite accessibility of the elites not being a linear process, evidence indicates that local elites (ward councillors) are usually inaccessible to the community and mostly unavailable (Ndasana, Vallabh & Mxunyelwa, 2022). From scholarly evidence, power dynamics and the behaviour of the elites shape how reconciliation can be approached, and they hint at what hinders or enhances reconciliation after the protest action. Further, since local elites are the first point of contact between the citizenry and the government, unequal power dynamics and unavailability of local elites imply compromised trust towards the government by the community.

Despite the evidence indicating the unavailability and behaviour of elites, instruments and measures have been recommended to ensure that the public does participate in local government decision-making, and the proper use of such instruments will minimise protest action. One such instrument or measure is public participation through ward committees in local government. Ward committees are community-based structures created to enhance local participation in municipal affairs (Dube et al., 2021). Despite the adoption of ward committees as modes of public participation, evidence indicates that participatory processes in South Africa are not transformative to elicit trust in the government institutions, hence this triggers protest action (Ragolane & Malatji, 2024). In establishing ward

committees, it must be noted that municipalities are not legally obliged to establish ward committees, and ward councillors must be chairpersons of ward committees (Sekgala, 2016). As ward committees are led by ward councillors, in theory, ward committees together with ward councillors are closer to the grassroots to hear community grievances and concerns; however, as councillors lead ward committees, this implies that agenda-setting and some decision-making powers are vested with the councillor as opposed to the ward committee. Further, evidence indicates that ward committees cannot deal with complex issues such as the Integrated Development Plan (IDP) and budgetary processes (Ragolane & Malatji, 2024). It is evident that utilising the system of ward committees does not change the perception of unequal power, but somehow perpetuates it as ward councillors are leaders of ward committees. Further, evidence indicates that ward committees do not sit at municipal council meetings, hence they have limited ability to influence decision-making (Dube et al., 2021).

4.2 Categories of protests

Protests in South African landscape have been categorised into different categories. The most common categorisation of protests is "orderly", "disruptive", and "violent" (Chiwarawara, 2023). Chiwarawara (2023) states that violent protests are characterised by property damage and people's injuries. Another category is introduced in categorising protests, namely protest events, lasting more than three days (Bekker, 2022). Further, protests can be categorised by their trigger. Protests triggered by dissatisfaction with municipal service provision are termed service delivery protests (Wöcke et al., 2023). Wöcke et al (2023) add a sub-category of service delivery protests, which are gangsterism-type protests where small groups of individuals emerge out of the social protest groups claiming to be local business forums and issue threats and demands to companies. These groups were seen as opportunistic and taking advantage of the situation. However, as protests are commonly categorised as 'orderly', 'disruptive' or 'violent', we believe that all protests in the peripheries and in South Africa are disruptive, regardless of the cause or trigger. A protest can be orderly, disruptive, or violent, as all protest actions disrupt the normality.

4.3 Cause of protests in the peripheries

In the peripheries, different factors trigger protest action. Behavioural factors are associated as triggers of protest action, such as perceived and real corruption, nepotism and incompetence by municipal officials (Ragolane & Malatji, 2024). Ragolane and Malatji (2024), on top of behavioural factors, indicate that structural factors also trigger protests, such as lack of basic services, poor infrastructure, lack of housing, inadequate job opportunities, lack of accountability of local councillors, inequality, and a general feeling of alienation from the structures of democracy. Some causes of protests are linked to the behaviour of leaders, while other factors are outcomes of the complex interplay of economic and policy variables. The authors also add that the slow pace of service delivery is one of the triggers.

Other scholars argue that the above-mentioned factors and a combination of factors trigger protest action in the peripheries. Poor service delivery in the peripheries, corruption, unemployment, poverty, leadership, political indifference, lack of accountability and improper use of funds have been identified to trigger protests (Damoah, 2023). Other identified factors include dissatisfaction with service provision, unemployment and poverty in the peripheries, and a lack of communication with ward councillors (Ndasana et al., 2022; Xaba et al., 2024). However, not all protests are triggered by structural factors mentioned above, as demarcations of municipal boundaries trigger some protests, as communities will object to these demarcations, and such objections are accompanied by protests (Netswera & Nealer, 2020). Although ward committees enhance public participation, local community exclusion in municipal decision-making triggers protests (Thusi et al., 2022). Mamokhere (2023), in agreement with the abovementioned factors, mentions unemployment, poor housing, water and sanitation, electricity, corruption, municipal administration, health, and crime as causes of the protests. Deducing from the mentioned factors, it is evident that elite behaviour concerning quality, good governance and ethical leadership changes when the peripheries are concerned. Further, as factors such as poverty, unemployment, and inequality trigger protests, this indicates that different spaces have different levels of economic performance in a

way that triggers protests in the peripheries as opposed to the core and suburban spaces. Lastly, the protests in the peripheries are triggered by a complex interplay of factors; however, the factors mentioned above are the most cited reasons for protests.

4.4 Attributes of protests in the peripheries

Having established the triggers of protests and their categories, some factors are key attributes to protest action in the peripheries. As much as evidence indicates inadequate leadership to facilitate development in the peripheries as opposed to the core spaces, concerning protests, evidence suggests otherwise. The first attribute that has been observed in South Africa, especially prevalent in the peripheral spaces, is that citizens are not satisfied with their involvement in local government's decision-making, despite ward committees being utilised as a mechanism for public participation (Ragolane & Malatji, 2024; Matyana & Sibiya, 2025). Other evidence indicates that, citizens have low level of interest in municipal politics as opposed to national politics, and this manifest through low participation in local government elections, and this occurs in the context where there is rife political interference in local government and citizens are not consulted adequately (Netswera & Nealer, 2020; Myeni et al., 2024). These attributes form the background of protest action in the peripheries. These attributes imply that communities have low trust in local government.

Some actors are collectively observed to initiate protests in the peripheries; however, these actors do not share the same characteristics besides residing in peripheral spaces. Community movements facilitate protests in the peripheries and are constituted by members of different political organisations, thus giving them an apolitical character (Paret, 2024; Sinwell, 2023). Historically, community movements were deemed as opposing the government during the presidency of Thabo Mbeki (1999 to 2008) (Bond & Mottair, 2013).

The other attribute present in the peripheral protests is using different conduits and nodes to facilitate protest action. Concerning conduits, social network services such as Facebook, Twitter, and WhatsApp serve as nodes and conduits utilised by political actors and activists to advance their agenda and propaganda to influence people through online participation (Mathe & Motsaathebe, 2022). Mathe and Motsaathebe (2022) warn that social media platforms are usually not utilised for meaningful political discussions or rational debate; participants are expected to adhere to the set agenda instead of independent thought.

The other attribute of protests in the peripheries is the utilisation of state-sponsored violence against the protesters. The concept of state-sponsored violence has characterised protest action in South Africa and also has characterised lived experiences for the Black majority in South Africa, albeit in different forms. Harden and Deligio (2021) state that state-sponsored violence is a violence committed by the members of the armed forces (police and military) against civilian victims, and there is an element of race involved in state-sponsored violence. The primary characteristic of state-sponsored violence is the response when the citizenry commits acts which are deemed to be revolt, rebellion, uprisings or misbehaviour; the state responds by violent action which includes the use of non-lethal force, beatings, arrests and imprisonments and at times the use of lethal force (Togarasei, 2022). Ntini and Mdlalose (2021) posit that the state is conceptualised as having the monopoly to exercise violence over its population within its territory. In South Africa, state-sponsored violence has been one of the triggers of protest action, and evidence indicates that protests are concentrated in the peripheries; hence, state-sponsored violence is a peripheral occurrence (Bonga, 2021). It is not only during protest actions that state-sponsored violence is utilised in South Africa. During the transition to the democratic era, state-sponsored violence was utilised by the apartheid government in South Africa, as the government supported the Zulu nationalist political organisation, Inkatha Freedom Party (IFP), which warred against the political forces aligned to the United Democratic Front (UDF) and the African National Congress (ANC). The transition era violence was largely based in the peripheral spaces of Gauteng (former Pretoria-Witwatersrand-Vaal, or PWV) and KwaZulu-Natal (former province of Natal and KwaZulu homeland). The state-sponsored violence of the transition era utilised private companies, covert operations and homelands' police and military regimes (Evans, 2024). Further, the use of state-sponsored violence

was observed during the COVID-19 pandemic in South Africa, when the state sanctioned the employment of armed forces to enforce lockdown rules, which was more pronounced in the peripheries (Reed & Xaso, 2022). Considering that in South Africa, white minority governments during both colonial and apartheid eras utilised state-sponsored violence to thwart opposition from the Black population, and state-sponsored violence was utilised during the transition era, this implies that the democratic government inherited institutions that were characterised by violence against the majority, which is the Black African population. As the government transitioned from apartheid to democracy, the character of violence remained; hence, state-sponsored violence has been utilised in the peripheries in the form of repression during protest actions. Reed and Xaso (2022) note that the police have utilised violence against Black and Coloured populations in the country, and this has continued into the contemporary democratic era. State-sponsored violence in the form of repression has been one of the characteristics of protest action in the peripheries in South Africa's democratic era, which also necessitates the need to deal with complex intergenerational trauma as a result of violence that has been unleashed on the Black majority.

The modus operandi of reporting protests by mainstream media is another attribute concerning peripheral protests. Protests covered by the mainstream media are based on the size of the protest, geography (especially main towns and cities), and the dramatic nature of the protest. As the media is selective in reporting on the protests, this results in protest activity being viewed in a negative light. The public views protesters as threats to the stability and democracy (Chiwarawara, 2023). Chiwarawara (2023) further posits that while mainstream media's hype about violence is understandable, given the desire to sell newsworthy stories, this is often misleading because more orderly and 'peaceful' protests do not receive the same coverage as 'violent' protests. It is not only media reporting that can be deemed problematic in reporting protest activity. Chiwarawara (2023) and Bekker (2022) point out the biases of data sources concerning protests in South Africa, the data from different organisations and the security apparatus. The Incident Registration Information System (IRIS), which is maintained by the South African Police Service (SAPS) Crime Combating Operations' Visible Policing Unit (VPU), records "crowd incidents", which are inclusive of other events such as social, religious and sporting events apart from protests (Chiwarawara, 2023). Bekker (2022) indicates that the size of the protests is a factor that is sometimes not considered when reporting about protests, thus introducing biases. Bekker (2022) further argues that between 2007 and 2009, protest action was underreported.

4.5 Reconciliation between elites and the community

Having established our thesis concerning protests in the peripheries in South Africa, and having determined that protests are disruptive and tend to be violent, we turn our attention to reconciliation. What is reconciliation, and why is it necessary? Peña (2022) defines *reconciliation as a process of building and normalising good relations between states, groups, organisations and individuals following severe reactions to incidents and preventing future incidents from occurring*. Deducing from the high incidence of protest activity in South Africa, this implies a need for reconciliation vis-à-vis protest action in the peripheral spaces.

As established, reconciliation prevents future incidents from occurring, and Wasserman et al. (2018) establish an argument concerning media coverage of protest action in the peripheries. Media coverage can amplify the voices in the peripheries or silence them by portraying protests as illegitimate and undemocratic. South African media has largely done the former as it largely reflects the elite perspective. Therefore, perception creation is used to further elite perspectives where protests look savage and uncivilised, thus thwarting avenues for reconciliation. Despite media coverage of protests being pro-elite, Chiwarawara (2023) brings another dimension that disproves the elite perspective concerning protests. Peripheral communities before protest action usually exhaust all peaceful avenues and only resort to protests and violent tactics after the failure of peaceful avenues. Chiwarawara (2023) further states that protestors usually avoid violence; violence in protests is often unplanned and is usually triggered by police's heavy-handedness. Damoah (2023) states that police brutality has adverse effects as it endangers infrastructure, including buildings, streets, clinics, schools, and other public facilities that are not being

used for protest. Careful consideration of the statements by Chiwarawara and Damoah reveals that the police are utilised as a buffer between elite interests and peripheral communities regarding protest action, while the media approach thwarts reconciliation

Since community movements drive protests in the peripheries, this has led to another measure being utilised instead of pursuing reconciliation. Transactional activism allows state actors to make promises of service provision and ignore them. Paret (2024) observed an incident where the then-ruling party, the African National Congress (ANC), incorporated community activists into a housing project, thus effectively muting any opposition. Building from this observation, Paret (2024) made further observations concerning the ANC. The ANC has dominated the South African political landscape between 1994 and 2014, securing 60% of the vote, and this domination correlated with issues such as corruption, patronage and authoritarianism. Although the ANC has been the dominant party, its dominance has been declining, as it declined from 70% in 2004 to 62% in 2014. At the time of this writing, the ANC's support stood at 40%, forcing it to enter into a coalition government, which was dubbed the Government of National Unity. Paret (2024) states that the decline of the ANC was evident in the 2016 local government elections, where it lost control of metropolitan spaces such as Johannesburg, Tshwane, Ekurhuleni and Nelson Mandela Bay, which are key metropolitan spaces. The ANC's decline is attributed to the formation of political organisations such as the Congress of the People in 2009 and the Economic Freedom Fighters in 2013 (Paret, 2024). The ANC's misfortunes did not stop in 2016, as it had lost 17 percentage points within five years after the 2019 national elections, and lost control of the most populous provinces in South Africa, namely Western Cape, KwaZulu-Natal and Gauteng, which raised the questions of sustainability (Everatt, 2024). The recent loss of the ANC in the 2024 elections can be primarily attributed to the formation of the political party Umkhonto weSizwe. Everatt (2024) argues that the ANC is acquiring a rural character in the urbanising country, as it has lost control of most strategic urban spaces. Concerning the use of transactional activism to minimise protests while disregarding reconciliation, the ANC has been a crucial factor in this phenomenon as it has largely controlled the state machinery, which now begs a question on how transactional activism will unfold given the different political dynamics as the ANC has entered into a coalition government. Further, the emerging political dynamics raise questions on whether the new coalition government will prioritise reconciliation with peripheral communities following protests.

Another angle of scrutinising reconciliation is observing how the state treats specific spaces. Evidence indicates that protests in urban capitals and major cities threaten leaders, and they use non-lethal means to suppress such protests. In contrast, they use more violent means in rural or secondary towns and urban peripheries (Christensen, 2018). Different approaches are utilised by the state actors in different spaces, indicating that reconciliation is not a top consideration for state actors.

Conclusions

Concerning the social strata in South Africa, evidence points out a bifurcation of classes, which is more pronounced when elites are compared to the peripheral communities. This bifurcation runs so deep that one social stratum exists in one of the continuum and the other stratum exists on the other end, with the other middle falling in between. When the peripheral communities protest at the other end of the continuum, the elites at the opposite end see no need for reconciliation with the peripheral communities; however, they are willing to unleash coercive measures to thwart protest action and identify certain leaders in the peripheries and co-opt them into a different class, thus thwarting reconciliation and minimising protests. This analogy explains why protest action in the peripheries suddenly erupts and subsides, resembling popcorn, hence earning the nickname "popcorn protests". Deducing from Christensen (2018) that heavy-handedness is utilised when protests threaten the extraction of natural resources, this indicates the willingness by the elites to employ state-sponsored violence in the form of police action while reconciliation is ignored.

However, concerning reconciliation between the elites and communities, it is not clear from the existing literature who is responsible for reconciliation. The extant literature is further unclear on which models or approaches can be utilised to reconcile the elites and peripheral communities after the protest action.

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Sandile Blessing MKHWANAZI

ORCID ID: <https://orcid.org/0000-0002-5842-0046>

Mandisi MATYANA

ORCID ID: <https://orcid.org/0000-0001-6928-4724>

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THE CIRCULAR BLUE ECONOMY IN EGYPT: OPPORTUNITIES FOR REGIONAL COOPERATION AND INTEGRATION WITH MEDITERRANEAN COUNTRIES FOR SUSTAINABLE DEVELOPMENT

Leonardo Piccinetti ¹, Tarek Y. S. Kapiel ², Nahed Salem ³, Trevor Uyi Omoruyi ⁴,
Alexia Massa Gallucci ⁵, Maghraby Khalil Elseify ⁶, Alaa A. El-Bary ⁷,
Mohamed Ramadan A. Rezk ⁸

^{1,6}*Sustainable Innovation Technology Services Ltd, Ducart Suite, Castletroy, Ireland*

²*Cairo University, Giza, Egypt*

^{3,8}*Academy of Scientific Research and Technology (ASRT), 11516, Cairo, Egypt*

⁴*Chester Business School, Queens Park Campus, Chester, United Kingdom*

⁵*Blue EcoTech Ltd., Malta, Italy*

⁷*Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*

E-mails: ¹leonardo@sinnovations.org; ²tkapiel@sci.cu.edu.eg; ³nahedelashkar.asrt@gmail.com; ⁴t.omoruyi@chester.ac.uk;
⁵alexia@blueecotech.eu; ⁶maghraby.sites@gmail.com; ⁷aaelbary@aast.edu; ⁸mramadan79@gmail.com

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Abstract. This study examines the possibility of the Circular Blue Economy in Egypt to support sustainable development and the usage of its renewable resources, focusing on possibilities for regional collaboration, particularly in the Mediterranean region. The study's methodology was an analysis of missing policies, identifying key actors, and an expert survey to identify future collaborations and opportunities, which included 20 experts from diverse sectors. Current policies in Egypt (e.g., Egypt Vision 2030) and the Mediterranean region were analyzed against the Sustainable Development Goals (SDG 14) and regional initiatives such as BLUEMED and SwitchMed, highlighting shortcomings in cooperation, investment, and environmental measures. The main parties, including the Egyptian government, the Union for the Mediterranean (UfM), the private sector, and local communities, were grouped according to their level of interest and influence. Findings indicate that Egypt's strategic location and extensive coastline are suited to drive regional efforts in maritime tourism, aquaculture, and maritime transport. Yet, problems, including marine litter and underfunding, continue. Experts also support the creation of regional cooperation platforms and joint pollution monitoring systems. The paper concludes with policy recommendations to integrate circular economy concepts into government strategies, strengthen collaboration across the region, and establish a collaborative and innovation-based ocean governance model. The paper presents new ideas to support regional integration and suggests additional studies on sustainable financing mechanisms.

Keywords: Circular Blue Economy; Egypt; Mediterranean; Sustainable Development; Regional Cooperation; Policy Gap Analysis

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JEL Classifications: O1, O55

1. Introduction

The Circular Blue Economy (BCE) combines ideas from both the Blue Economy (BE) and the Circular Economy (CE) to encourage long-term ecological balance and efficient use of resources in marine and coastal environments. The blue economy focuses on the responsible utilisation and management of ocean resources to

boost the economy, create jobs, and support communities while maintaining healthy and balanced marine environments. It covers several industries, including fisheries, aquaculture, maritime transport, coastal tourism, renewable ocean energy, marine biotechnology, seabed mining, and marine conservation (Graziano et al., 2022; Choudhary et al., 2021; Junceda-Mena et al., 2023; Shan et al., 2023). First introduced by Belgian economist Gunter Pauli in the mid-2000s, the concept of the blue economy points to the ocean's potential to support greener, more equitable development (Ahmed & Thompson, 2018). The Blue Economy has emerged from an increasing awareness of the role of the oceans in national economies, alongside the need to protect the oceans (Winder & Heron, 2017; Garland et al., 2019).

On the other hand, the circular economy focuses on reducing how much we rely on nonrenewable materials by encouraging reusing, recycling, and renewing materials across the life of products. It seeks to reduce waste, emissions, and energy consumption while fostering sustainable production and consumption models (Tolio et al., 2017; Junceda-Mena et al., 2023; Rezk et al., 2023). The circular economy in the marine context involves designing out pollution, keeping materials in use, and helping ecosystems recover. This approach plays a key role in sectors such as fisheries, aquaculture, maritime transport, offshore energy, and tourism (Barroso et al., 2022). The circular approach in marine sectors offers substantial potential to reduce the ecological footprint of blue economy activities by promoting innovative practices such as fisheries waste valorisation, repurposing plastic debris, and the design of biodegradable aquaculture gear. (Francis & Herat, 2020). This model matches broader global efforts for sustainability, particularly the United Nations Sustainable Development Goals (SDGs), including SDG 12, focused on using and producing responsibly, and SDG 14, which aims to protect and wisely use oceans. (Di Vaio et al., 2024)

The Circular Blue Economy (CBE) is an integrated approach that not only helps use marine resources responsibly but also significantly reduces environmental impact by bridging resource gaps, improving the reuse and recycling of materials, and supporting new, green, and climate-friendly ways of doing business (Tucci et al., 2021; Fernandez-Gonzalez et al., 2024). It encourages systemic changes across the marine value chain by embedding eco-design principles, life cycle thinking, and regenerative resource use into coastal and ocean-based industries. Furthermore, the CBE initiative supports creative reuse and turning marine materials into valuable products such as oyster shells, seaweed biomass, seagrass beach wrack, and fishery by-products, which are being incorporated into bio-based plastics, fertilisers, pharmaceuticals, and green building materials (Summa et al., 2022). The scope of the Circular Blue Economy thus extends well beyond conventional recycling practices; it includes the development of circular water markets, energy-efficient desalination systems, blue biorefineries, and closed-loop wastewater management solutions, , which are increasingly recognized as integral components of building a sustainable and resilient blue economy while reducing the amount of waste produced by blue industries (Firoozi & Firoozi, 2022).

The blue economy includes old and new industries that are essential for boosting new ideas, eco-action, and development, particularly in the Mediterranean region, which has a vast 46,000 km coastline and sea-based assets worth around €4.7 trillion. It covers just 1.5% of Earth but holds remarkable natural life and marine diversity (Biuksane, 2022; Sardinha, 2024). Among the core sectors of the blue economy, fishing and aquaculture play a critical role in ensuring food security and providing livelihoods, especially within coastal communities (Sardinha, 2024). Coastal and maritime tourism significantly contributes to the economy by capitalising on the region's unique natural and cultural heritage to create jobs and generate income (Figueiredo et al., 2023). Maritime transport plays a central role in trade and logistics, enhancing economic integration and facilitating regional development (Olteanu & Stinga, 2019). Furthermore, the growth in clean marine energy like wind and wave power shows how key it is to go green and reduce pollution (Roberts & Ali, 2016). In 2022, EU blue industries created employment for nearly 4.82 million people, made €890.6 billion in revenue, and added €250.7 billion in value (Table 1). Projections for 2023 suggest continued growth, with these sectors contributing €263 billion to the

EU's gross value added (GVA) and employing approximately 4.88 million people, highlighting the increasing economic significance of the blue economy across the European Union (European Commission, 2025).

Table 1. European blue economy established sectors, main indicators, 2022

Indicator	EU Blue Economy 2022
Turnover	€890.6 billion
Gross value added	€250.7 billion
Gross surplus	€120.6 billion
Employment	€4.82 million
Net investment in tangible goods	€8.8 billion
Net investment ratio	3.5%
Average annual salary	€27 016

* Turnover is calculated as the sum of turnover in each sector

Source: European Commission, 2025

Building upon the importance and variety of industries of the blue economy, recent strategies are now more connected to international green efforts, most notably the United Nations Sustainable Development Goals (SDGs). These evolving strategies highlight the rising in understanding of the seas' key role in advancing long-term innovation and ecological balance. SDG 14, which aims to protect and wisely use marine resources, has become a core part of ocean economy planning (Steven et al., 2019; Wang et al., 2022; Ha, 2024). In this context, the European Union has intensified its commitment to safeguarding marine biodiversity while promoting sustainable blue growth and employment. In line with broader environmental goals such as the European Green Deal and the Farm to Fork Strategy, the European Commission introduced strategic guidelines for the aquaculture sector (2021–2030) to foster resilience, competitiveness, and environmental sustainability. Central to these guidelines is promoting organic aquaculture through innovative feed practices, including reducing limiting use of ocean-caught ingredients and using other protein alternatives like seaweed, insects, and leftover materials from seafood processing factories (European Commission, 2021).

At the regional level, efforts to advance a sustainable and resilient blue economy have been reinforced through coordinated policy actions and innovative environmental initiatives, the Union for the Mediterranean (UfM) renewed its focus on ocean sustainability by issuing a major political declaration on February 2, 2021. Building on the foundation laid in 2015, this declaration emphasises post-pandemic recovery and long-term sustainability in sectors such as marine governance, scientific research, sustainable fisheries, climate-resilient maritime transport, and strategic investment (Union for the Mediterranean, 2021). Complementing this commitment, the BLUEMED Initiative serves as a key platform for promoting science-policy-industry collaboration across the Mediterranean. Its Strategic Research and Innovation Agenda (SRIA) supports circular economy practices, marine innovation, and joint actions that facilitate Egypt's participation in sustainable blue growth (Cappelletto et al., 2018). Similarly, the Barcelona Convention, under United Nations Environment Programme / Mediterranean Action Plan (UNEP/MAP), offers a binding framework for protecting the Mediterranean marine environment. Egypt engages with its protocols on pollution control, biodiversity, and coastal zone management, particularly through the Regional Plan for Marine Litter Management, which aligns with national efforts to advance circular marine waste strategies (Galgani, 2019).

The Mediterranean Sea is one of the world's most polluted seas with plastic pollution, particularly in areas near densely populated coastlines, river estuaries, and regions with limited water exchange (Cózar et al., 2015). Mediterranean nations collectively generate approximately 24 million tons of plastic waste annually, yet only 72% of this waste undergoes proper treatment through formal systems, with noticeable differences in effectiveness across countries. Around 20.4 million tons, roughly 85% of the total, is collected, while the remaining 3.6 million tons (15%) remain uncollected and likely to leak into the environment (Dalberg Advisors, 2019). As illustrated in Figure 1, all countries in the region contribute to some extent to improperly managed

plastic waste. However, due to factors such as consumption levels, economic scale, and the efficiency of waste infrastructure, Egypt (42.5%), Turkey (18.9%), and Italy (7.5%) are ranked as the top sources of poorly managed plastic trash in the region (Kaza et al., 2018).

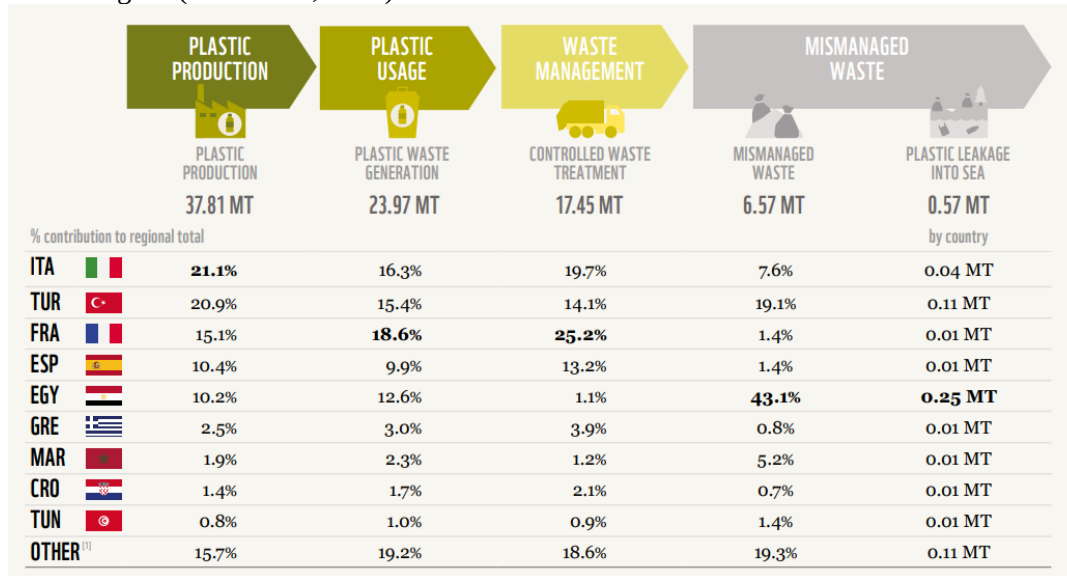


Figure 1. Overview of the Mediterranean Plastic Lifecycle and Its Contribution to Marine Pollution

Source: Kaza et al., 2018

Egypt plays a key role in how plastic is made and handled in the Mediterranean, producing 10.2% of all plastic and generating 12.6% of the overall waste in the region. However, the country is facing serious problems with plastic disposal. Even though it doesn't produce or use as much plastic as some countries, Egypt accounts for 43.1% of the region's mismanaged plastic waste, the highest among all countries, and about 250,000 tons end up in the sea, representing nearly 44% of the region's total plastic leakage. This highlights why it is pivotal to boost the circular blue economy.

A clear case showing how circular blue economy ideas are applied in the Mediterranean area is Italy's Life Muscles Project (2021–2025), which aims to reduce plastic waste caused by mussel farming by introducing sustainable practices such as recycling mussel nets and using bio-based materials like MATER-BI. This approach deals with the major problem associated with this industry of using 700 to 1,000 tons of nets used annually, a portion of which, approximately 8 to 9 tons, usually ends up polluting the sea (Pietrelli, 2022). Similarly, the Ocean Wise Project (2021) addresses problems caused by using EPS boxes in fishing by promoting biodegradable alternatives and setting up return-and-reuse systems. These projects exemplify actionable strategies for enhancing circularity and reducing ecological impact within the maritime supply chain (Savoca et al., 2022).

New developments in the region show how Egypt could lead the shift toward a more sustainable marine economy. Geographically situated at the crossroads of Africa, Asia, and Europe, Egypt possesses approximately 3,000 kilometres of coastline comprising 1,000 kilometres along the Mediterranean Sea, 2,000 kilometres along the Red Sea and the Gulf of Aqaba and a network of 55 seaports containing 197 terminals spanning 37.5 kilometres (Gaber, 2022; Attallah & Attia, 2024). These geographic and infrastructural assets offer a strong foundation for developing a resilient blue economy. Nevertheless, even with these strengths, marine activities still make up just 2.2% of Egypt's GDP, showing that these ocean resources aren't being used to their full potential (Gaber, 2022; Attallah & Attia, 2024). Egypt's blue economy framework focuses on responsibly using sea and coastal resources, particularly within key sectors such as fisheries, aquaculture, and coastal tourism, which are instrumental for

national food security and economic diversification (Nguyen, 2024). To fully benefit from this sector, Egypt needs major policy changes at home and closer teamwork with other countries around the Mediterranean. Better cooperation means exchanging skills, setting shared environmental rules, and launching cross-border initiatives, thereby contributing to a more integrated and sustainable blue economy model at the national and regional levels.

This paper investigates the many opportunities Egypt has for developing its circular marine economy, focusing on how Egypt can work with nearby countries to promote sustainability. It aims to find what's missing in current policies, understand who's involved, analyse the main issues, and suggest practical solutions. By combining different tools and approaches, this research informs policymakers, regional organisations, and private sector actors working toward a more stable and eco-friendlier ocean future benefiting all countries around the Mediterranean Sea.

2. Methodology

This study used a research approach to investigate the Circular Blue Economy in Egypt to support sustainability and build stronger regional ties with Mediterranean nations. The methodology (included reviewing earlier research on the blue and circular economies, especially studies that connected the two, also involved identifying Egypt's strengths in the marine economy compared to other Mediterranean nations. a structured review was carried out to find what's missing in Egypt's key strategies, including Egypt Vision 2030 and the National Climate Change Strategy 2050 alongside regional initiatives such as BLUEMED, Plastic Busters, and programs under the Union for the Mediterranean related to the blue economy. This analysis looked at how well these strategies match the targets of SDG 14, (to find where improvements are needed in leadership, teamwork across borders, funding, and pollution management.

The study also identified and grouped the main players using their involvement and influence as a criterion. The classification included government institutions (e.g., Ministry of Environment, Ministry of Transport), regional organisations (e.g, Union for the Mediterranean), international partners (e.g., the World Bank, Global Environment Facility - GEF), along with the private sector, civil society organisations, and local communities. A diagram was created to show how these groups interact and where connections are missing. To explore how Egypt can work more closely with other Mediterranean nations in the future, a two-round Delphi questionnaire was sent to 20 experts in the blue and circular economy sectors. The questionnaire used Google Forms, exploring current policies, where investment could go, what environmental risks exist, and how countries might work together. The collected data was studied using basic statistics with SPSS software to spot shared views and differences in opinion. The study relied on direct responses from experts and existing sources like reports and academic studies.

3. Results and Discussions

3.1 Mapping the Sectors and Key Stakeholders of Egypt's Circular Blue Economy

3.1.1. Fisheries and Aquaculture

The fisheries and aquaculture sector in the Mediterranean plays a major role in the region's marine economy, generating more than 1.5 million tons of fish annually. Of this output, approximately 55% is caught directly from the sea and 45% is produced from aquaculture. The sector generates an estimated EUR 18 billion in revenues, with aquaculture accounting for roughly 60% and fisheries making up the other 40%. Furthermore, it provides jobs for over 700,000 people across the sector, with over 60% of jobs concentrated on fisheries and less than 40% in aquaculture-related activities. About 75,000 fishing boats operate in the region, with more than 750,000 tons in total vessel size (FAO, 2023). Jobs, both directly and indirectly linked to the sector in the region. Majority of the workers are based in border nations (Tunisia, Turkey, Egypt, Italy, Greece and Morocco) and with a strong prominence of workers in Small Scale Fisheries (about 62% of total employment in the sector although only

representing 26% of total revenue), usually run as small businesses, with little investment, and often owned and operated by families (FAO, 2022).

When evaluating the entire region, Egypt is central to developing the blue economy in the Mediterranean through its substantial fish production and expanding aquaculture industry. Fish production is a significant component of Egypt's national economy, helping to ensure food supply, jobs, and national income. The country produces approximately 1.9 million tons of fish annually, of which 1.6 million tons are sourced from aquaculture and 0.3 million tons from natural resources wild stocks (Mehanna, 2021). Egypt operates a fleet of 4,379 fishing vessels, making it one of the eight biggest fleets in the region. As illustrated in Figure 2, which shows the number of fishing vessels operating across Mediterranean countries, Egypt's fleet size is smaller than top countries like such as Tunisia (12,220), Greece (12,197), and Italy (9,651), yet it still ranks among the five main nations alongside Italy, Türkiye, Tunisia, and Algeria who together make up about 66% of the region's fishing power fleet (FAO, 2023).

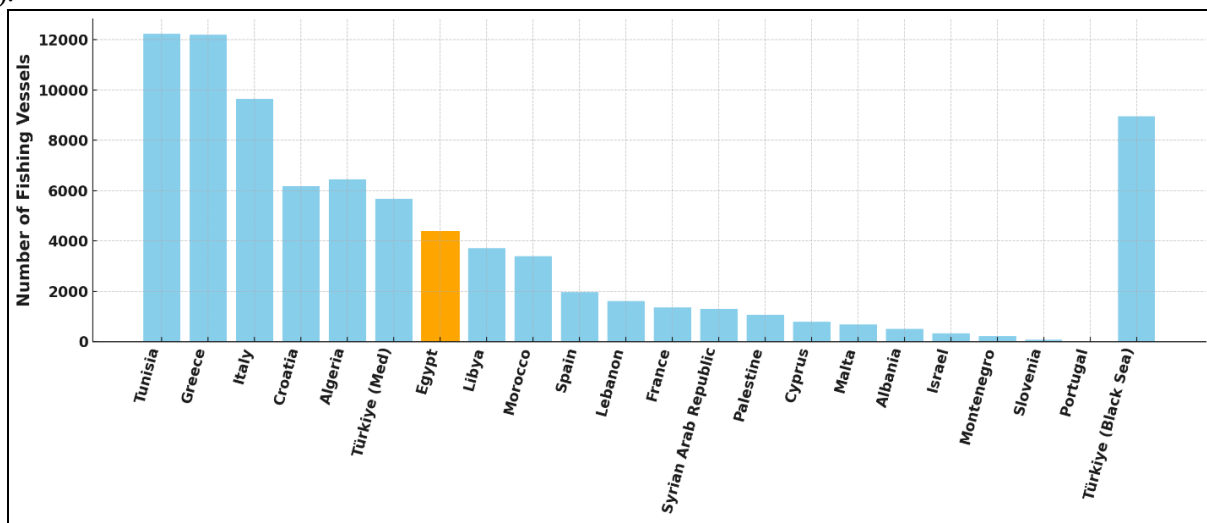


Figure 2. Number of fishing vessels operating across Mediterranean countries
Source: FAO, 2023

Egypt is going through a significant shift in managing its lakes and fisheries by setting up the new Lakes and Fish Resources Development Agency (LFRDA), taking over from the previous fisheries authority General Authority for Fish Resources Development (GAFRD). Operating under the Prime Minister's supervision, LFRDA plans to gather funding to support the long-term development of lakes and coastal areas to contribute to national development. In parallel, the Ministry of Agriculture and Land Reclamation (MOALR) introduced a long-term plan to improve eco-friendly fish production and support jobs, which was in line with new national laws and recent regulations. These efforts encourage teamwork between government and business, with a focus on helping small fishers through loans and fair policy tools.

3.1.2. Maritime Transport

Maritime transport continues to be a core part of ocean-based economics, comprising 90% of goods traded worldwide and helping to connect markets and create jobs (Randone et al., 2019). The Mediterranean Sea plays a unique geographic and trade role, connecting three continents Africa, Asia, and Europe and accommodating roughly 30% of global maritime trade and up to 25% of oil shipments. The corridor between the Suez Canal and the Strait of Gibraltar is one of the world's most heavily used and critical maritime passages. However, the high traffic density creates major environmental challenges, increasing risks of pollution and damage to sea life. In recognition of these challenges, the Mediterranean will soon become a special zone to limit ship emissions under

implementing MARPOL Annex VI starting May 2025, requiring cleaner fuel and pushing ships to adopt green technologies (Brewer, 2020; Alomar et al., 2025).

Egypt's position makes it a major player in maritime transport, primarily due to its stewardship of the Suez Canal, which handles one-tenth of world trade and over one-fifth of the global container movement (Guangqiang, 2022). Key ports such as Port Said, Alexandria, and Damietta function as a vital part in regional shipping, supported by national initiatives aimed at enhancing infrastructure and transport efficiency. Nonetheless, the country still faces problems like outdated ports, climate-related risks, and heavy use of oil-based energy. In response, Egypt has begun investing in smart port technologies, greener practices, and better connections with inland transport. Its engagement in regional frameworks such as the Mediterranean Maritime Strategy 2022–2031 and EU-supported decarbonization programs signals a strong commitment to align maritime growth with sustainable development goals. By promoting cleaner shipping practices, Egypt not only reduces its environmental footprint but also contributes to the long-term health of marine ecosystems and the sustainability of coastal economic activities (Dewan & Godina, 2024).

3.1.3. Coastal Resources

The 2021 Ministerial Declaration on the Sustainable Blue Economy (SBE) (Union for the Mediterranean, 2021) highlights how important maritime tourism near the sea is for the region's economy especially for those countries bordering the Mediterranean. This prominence comes from how easy it is to reach the coast and how busy coastal towns are. Nevertheless, the declaration also points out this industry's environmental and social downsides on coastal communities. The tourism sector contributes approximately 13% of total exports and 23% of the service sector in Mediterranean economies. On a global scale, the region accounts for nearly 35% of international tourist arrivals and 30% of tourism revenues, while accommodating 20% of the world's hotel capacity, comprising over 10,000 destinations, 600 ports, 100,000 hotels, and more than one million restaurants (ASCAME, 2022).

In Egypt, the areas where land meets the sea host rich and varied ecosystems that support a wide range of environmental and economic functions. The Mediterranean coast is distinguished by sandy beaches, coastal dunes, lagoons, mudflats, and seagrass beds, while the Red Sea coast hosts mangrove forests and coral reef systems, which are ecologically significant and contribute to the provisioning of ecosystem services. By the end of 2022, Egypt's 2,800 km coastline was home to approximately 22% of the country's total population of 104.4 million (CAPMAS, 2025), showing how important coastal areas are to for the economy and the society. These areas support a variety of strategic sectors, including maritime transport and ports, oil and gas exploration, industrial and energy production, aquaculture, and fisheries, in addition to infrastructure for desalination, wastewater treatment, and tourism-related services (Yoshijima et al., 2024). The presence of protected areas and ecotourism lodges further underscores the multifaceted value of these coastal and marine spaces.

In terms of economic valuation, Egypt's coastal and marine natural capital stock was estimated at approximately USD 233.4 billion in 2021, encompassing both the Mediterranean and Red Sea regions. This figure is calculated using a 25-year forecast of key resources, including active oil and gas reserves, fisheries, coral reefs, mangroves, and seagrass beds, adjusted for future value using a 3% rate (Figure 3). Although additional extractive resources such as salt, pearls, and black sand exist, they were excluded from the assessment due to insufficient data availability. Importantly, the valuation shows that fossil fuels far outweigh renewable resources in value: nonrenewable fossil fuels are valued at USD 209.7 billion, which is nearly nine times the value of renewable natural resources (USD 23.7 billion). The Red Sea is shown to have more wealth, contributing USD 133.6 billion in nonrenewables and USD 21.9 billion in renewables, largely due to its active oil and gas fields and extensive coral reef ecosystems, which together account for most of the country's valuable marine assets (Yoshijima et al., 2024).

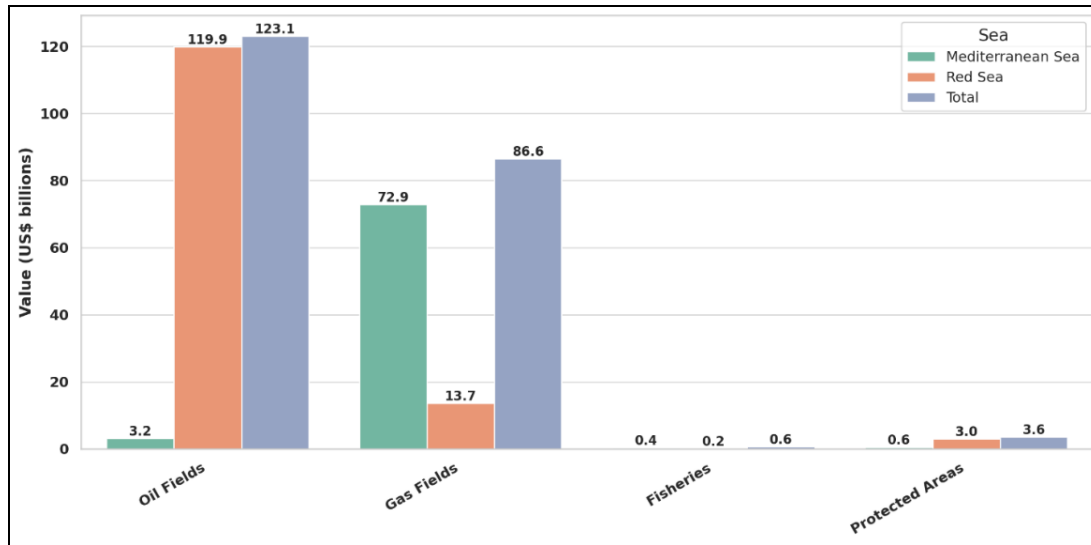


Figure 3. Egypt Marine Natural Resource Capital Stock, (in 2021 Prices US\$ billions)

Source: Yoshijima et al., 2024

3.1.4. Stakeholders in Egypt's Circular Blue Economy

The approach of involving stakeholders follows top global standards that have helped make circular blue economy efforts work well around the world. Countries such as Portugal, Norway, and Canada have demonstrated the effectiveness of integrated governance systems that combine efforts from government, science, business, and society in shaping practical and green solutions for the sea (OECD, 2021). In Egypt, a similarly comprehensive stakeholder framework is critical to advancing the circular blue economy, especially with a view of building stronger ties with other Mediterranean countries.

The key stakeholders (Table 2) encompass government entities, academic and research institutions, private sector actors, international organisations, civil society, and local communities. At the national level, ministries such as the Ministry of Environment, the Ministry of Transport, the Ministry of Tourism, the Ministry of Industry and the Ministry of Higher Education play critical roles in shaping regulatory frameworks, aligning policies with Egypt Vision 2030, and promoting blue innovation. Research centres like the National Institute of Oceanography and Fisheries (NIOF) and leading universities contribute to knowledge production and capacity-building in marine science and circular practices. Regional platforms such as the Union for the Mediterranean (UfM) and initiatives like BLUEMED act as facilitators of cross-border collaboration, policy harmonisation, and shared project development.

Meanwhile, NGOs and community-based organisations help bridge the gap between national policies and local implementation, particularly in areas related to marine conservation and sustainable coastal tourism. Private sector actors, including fisheries, aquaculture enterprises, and maritime transport companies, are essential for adopting circular practices, investing in eco-innovation, and creating job opportunities. Moreover, international partners such as the EU, UNDP, and FAO offer support, money, and tools to track progress aligned with the Sustainable Development Goals.

Table 2. Stakeholder Typology for the Blue Economy in Egypt and Regional Mediterranean Integration

Category	Stakeholders	Role
Government Entities	Ministry of Environment, Ministry of Transport, Ministry of Tourism, Ministry of Industry, Ministry of Agriculture (Fisheries), Suez Canal Authority, Lakes and Fish Resources Development Agency (LFRDA)	Policymaking, regulation, enforcement, financing, regional coordination
Regional Bodies	Union for the Mediterranean (UfM), BLUEMED Initiative, Barcelona Convention	Promote regional cooperation, joint projects, harmonise regulations across Mediterranean countries
International Partners	UNDP, FAO, UNEP-MAP, European Union (ENI CBC Med Program)	Funding, capacity-building, technical support, SDG 14 implementation assistance
Private Sector	Maritime tourism companies, port and transport companies, aquaculture businesses, offshore energy companies, tourism operators	Business operations, infrastructure investments, innovation in sustainable marine resource use
Research & Academia	Universities and research centres (e.g., Arab Academy for Science and Technology, National Institute of Oceanography and Fisheries (NIOF))	Research, innovation, scientific data production, marine biodiversity conservation
Civil Society & NGOs	Environmental NGOs, local fisherfolk associations, Nature Conservation Egypt, Youth-led environmental groups	Community engagement, awareness, local conservation, watchdog roles
Local Communities	Coastal communities in Alexandria, Port Said, Matrouh, Red Sea Governorates	Resource users, traditional knowledge holders, impacted stakeholders
Science & Innovation Bodies	Ministry of Higher Education and Scientific Research, Academy of Scientific Research and Technology, Science, Technology & Innovation Funding Authority	Research funding, innovation policy, linking academia with the blue economy needs
Financial Institutions	National banks, Global Environment Facility (GEF), World Bank, European Investment Bank	Funding sustainable projects, public-private partnerships, impact finance

Source: Authors

3.2. Gap Analysis of Egypt's Circular Blue Economy Policies: Alignment with SDG 14 and Mediterranean Initiatives

The Circular Blue Economy provides a new way to combine sustainable ocean use with circular practices like reuse and recycling, including waste minimisation, recycling, and the extension of product life cycles. While one or more countries are adopting this approach, positioning it as a pivotal pathway for sustainable marine development, its practical implementation in Egypt remains limited. This is primarily mentioned at a minimal level across different policies. This section analyses the policy and institutional gaps in Egypt related to the Circular Blue Economy, with a particular emphasis on their alignment with the Sustainable Development Goals (SDGs), notably Goal 14: Life Below Water. It explores how Egypt's plans align with important regional efforts, such as BLUEMED, SwitchMed, and Plastic Busters, which are widely seen as successful examples of marine protection and circular resource management.

3.2.1. Policy Gaps in Egypt's Vision and Climate Strategies for the Circular Blue Economy

Egypt Vision 2030 and the National Climate Change Strategy 2050 serve as the main guides for sustainable development and climate resilience. Both documents highlight key ideas such as environmental protection, innovation, and cross-sectoral coordination. However, neither clearly includes the circular blue economy as a standalone strategic priority, which results in several policy gaps. In Egypt Vision 2030, while climate action and resource efficiency are key themes, the circular blue economy is not treated as a defined area with its own frameworks or measurable objectives. Although the vision references sectors like coastal tourism, maritime transport, and fisheries, it lacks specific targets or policies for reuse, recycling, or waste reduction within marine value chains. Additionally, there are no systems to measure progress toward SDG 14 (Life Below Water) or clear ways to coordinate among ministries responsible for maritime affairs.

Similarly, the National Climate Change Strategy 2050 supports sustainable coastal management and nature-based solutions, but does not include circular economy practices in its climate mitigation or adaptation strategies. The strategy connects protecting marine life with the circular use of resources and does not offer funding support for innovation and infrastructure in marine circularity. Key circular solutions, such as wastewater reuse in aquaculture or recycling marine litter, are not included in Egypt's climate or waste plans, representing missed opportunities for cross-sectoral synergy. In advancing a circular blue economy in Egypt, it is essential to see how current national plans match the Sustainable Development Goals, particularly SDG 14: Life Below Water, which directly addresses marine conservation, sustainable resource use, and the ecosystem. The circular blue economy brings together eco-friendly use of oceans resources with circular practices such as waste reduction, reuse, and regeneration. To assess how supportive the current system is for such an approach, this review compares the extent to which key SDG 14 sub-targets are reflected in three major national strategies: Egypt Vision 2030, the National Climate Change Strategy 2050. Table 3 shows what is included or missing of SDG 14 components across these strategies and identifies areas with potential for further development to support a circular blue economy model.

Table 3. Alignment of Key SDG 14 Sub-Targets with Egypt's National Strategies

SDG 14 Sub-Target	Egypt Vision 2030	National Climate Change Strategy 2050	Alignment Notes for Circular Blue Economy
14.1 Reduce marine pollution	General reference to environmental protection	Indirectly addressed through water pollution control strategies	Further integration needed for marine-specific pollution (plastics, nutrients, wastewater)
14.2 Protect and restore marine/coastal ecosystems	Ecosystem resilience and biodiversity objectives included	Biodiversity conservation addressed under the adaptation goals	Supports coastal ecosystem preservation; can be expanded with targeted restoration programs
14.3 Address Ocean acidification	Not addressed	Not addressed	Requires inclusion of ocean pH monitoring and related scientific research
14.4 Regulate harvesting, end overfishing	Reference to sustainable resource use	Covered under ecosystem and biodiversity goals	Legal framework exists (Law No. 124/1983 and Law No. 146/2021) regulating fishing seasons, gear, and licensing across marine and inland fisheries. Where more specific policies could be developed to support sustainable fisheries management.
14.5 Conserve coastal and marine areas (10%+ MPA target)	Protected areas established under Law 102/1983	Aligned with biodiversity protection but no direct MPA targets	National MPAs cover ~10% of marine/coastal zones; continued development supports international commitments
14.6 Prohibit harmful fisheries subsidies	Not addressed	Not addressed	Alignment with global trade and sustainability frameworks (e.g. WTO) presents future opportunity
14.7 Economic benefits from sustainable marine use	General goals on innovation and value chains	Included under sustainable economic development	Potential to enhance blue economy sectors: aquaculture, marine tourism, biotechnology
14.a Support marine research and tech transfer	Promote innovation and scientific research	Science, research, and awareness included in Goal 5	Could be strengthened by supporting marine-specific data systems and research infrastructure
14.b Access for small-scale fishers	Not addressed explicitly	Not addressed	Opportunity to integrate artisanal fisher rights into legal frameworks and development plans
14.c Implement international law (UNCLOS, ocean governance)	Egypt is a party to UNCLOS and regional conventions	Not explicitly referenced	Could benefit from stronger incorporation of international marine law into national strategy

Source: Authors

3.2.2. Policy Gaps in the Egyptian Context and Alignment with Mediterranean Blue Economy Initiatives

Despite Egypt's clear efforts toward green development and adapting to climate change, several policy gaps hinder the full integration of circular blue economy principles within national strategies and their connection to major regional efforts. The Union for the Mediterranean (UfM) has launched initiatives supporting regional cooperation in key blue economy areas such as maritime transport, tourism, renewable energy, and fisheries. Egypt is strongly involved in these regional efforts, highlighting its regional commitment. There is room to better match Egypt's plans with UfM goals by developing national funding mechanisms, increasing SME and startup participation, expanding technical and administrative capacities, and creating clear systems to track progress and monitor funding access and program implementation.

The **BLUEMED** is an EU-led program focused on research and innovation, with the objective of promoting long-term development and employment in the blue economy across the Mediterranean region. It encourages a cooperative approach between EU and non-EU Mediterranean countries to address shared marine and maritime challenges, emphasising knowledge generation, technological progress, and environmental protection. In the Egyptian context, several national priorities match the goals of the BLUEMED Initiative, particularly in environmental sustainability and coastal development. Better aligning Egypt's efforts with BLUEMED's results can further enhance regional collaboration and knowledge exchange. The initiative also presents valuable opportunities for academic and research institutions to engage in collaborative innovation. Establishing a national coordination mechanism could support the integration of BLUEMED outcomes into Egypt's blue economy and circularity frameworks, facilitating the translation of shared outputs into actionable programs

SwitchMed is a European Union-funded program that supports the shift toward sustainable consumption and production patterns across Southern Mediterranean countries. Its blue economy component focuses on green innovation, building circular systems, and sharing knowledge across the region in key sectors such as fisheries, maritime transport, and coastal industries.

In Egypt, there is notable potential to enhance engagement with the SwitchMed program by developing a national action plan for the circular blue economy aligned with its objectives. Giving small businesses better access to funding and expertise, increasing participation in pilot projects, and adapting program toolkits to the local context would further advance this engagement. Improved institutional coordination across key ministries, such as environment, transport, and agriculture, would also support more effective application of SwitchMed's cross-cutting strategy.

Table 4. Policy Gaps and Alignment with Mediterranean Blue Economy Initiatives in Egypt

Mediterranean Initiative	Egypt's Current Engagement	Policy Gaps	Opportunities for Alignment
Union for the Mediterranean (UfM)	Active participation in UfM dialogues and platforms	- National funding for circular blue economy initiatives is yet to be designated. - Strategic alignment with UfM priorities remains limited. - Private sector participation, especially SMEs, is still emerging. - Technical and institutional capacities require further development. - No evaluation mechanism currently tracks funding uptake.	- Develop national funding lines for circular blue economy - Align national strategies with UfM priorities - Encourage SME/startup participation - Build institutional capacity and introduce evaluation mechanisms
BLUEMED Initiative	Partial alignment with environmental and coastal priorities	- Structural alignment with BLUEMED outputs can be further strengthened. - Participation from universities and research institutions remains limited. - A national coordination and follow-up mechanism has not yet been established. - Circular economic practices in the marine sectors are in the early stages of adoption	- Establish a national platform to coordinate BLUEMED integration - Promote academic and research involvement in blue innovation - Align circular economy efforts with BLUEMED focus areas

Mediterranean Initiative	Egypt's Current Engagement	Policy Gaps	Opportunities for Alignment
SwitchMed Initiative	Some involvement in initiatives, but lacks visibility and strategic coordination	- A national action plan aligned with SwitchMed objectives is yet to be developed. - Financial and technical support for SMEs in circular models remains limited. - Program materials require adaptation to local contexts. - Cross-ministerial coordination is currently limited. - A monitoring and evaluation system has not yet been established.	- Create a national circular blue economy action plan - Develop SME support aligned with blue circularity - Adapt SwitchMed models to Egypt's context - Enhance cross-sector coordination and tracking

3.3. Results of the Delphi

To identify the main focus areas and tools for policymaking to advance Egypt's circular blue economy, a Delphi study was conducted involving 20 experts from varied fields and areas of expertise. Participants were selected through purposive sampling to ensure representation across key domains, including marine policy, environmental economics, coastal and spatial planning, circular economy, and regional cooperation within the Mediterranean. The Delphi method was employed in two stages of repeated consultation, enabling the gradual refinement of expert consensus.

3.3.1 Perceived Challenges and Barriers to Egypt's Circular Blue Economy

As illustrated in Figure 4, experts identified a clear set of barriers limiting Egypt's ability to transition toward a circular blue economy. The most critical challenge cited was the lack of funding and investment mechanisms (83%), followed closely by a weak regulatory framework (77%) and poor inter-agency coordination (63%). These structural and institutional obstacles reflect a fragmented policy environment, where practical implementation remains constrained despite national ambitions for green development. Experts noted that without reliable and accessible financing tools, such as blue bonds or marine investment facilities, projects aimed at circular marine practices are unlikely to scale. Furthermore, the absence of a cohesive regulatory framework and the siloed nature of government institutions hinder synergies across coastal, environmental, and economic sectors. Additional barriers identified include limited stakeholder engagement (57%) and gaps in public awareness (43%), pointing to stronger community involvement, inclusive policy dialogues, and public education on the benefits of circular blue practices. A minority of experts (17%) also emphasised the lack of a long-term strategy, highlighting the importance of institutional foresight and continuity in marine policy planning. These findings suggest that while Egypt has committed to sustainability through initiatives like the National Climate Change Strategy 2050, a dedicated circular blue economy roadmap remains underdeveloped.

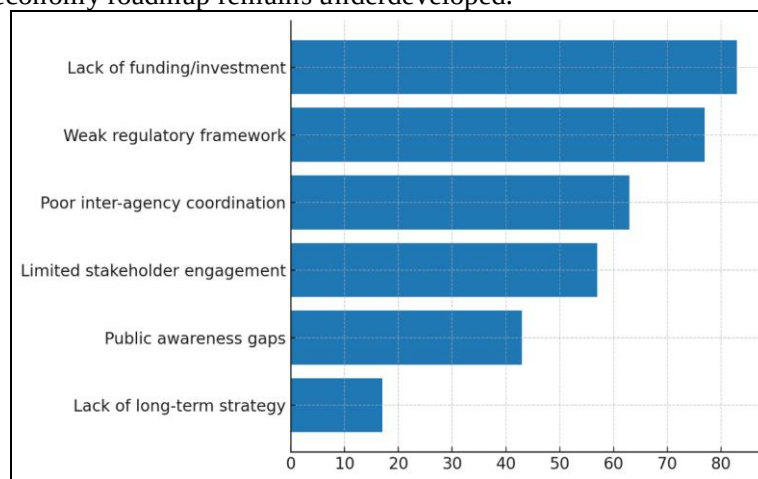


Figure 4. Perceived Barriers to Circular Blue Economy Development in Egypt According to Expert Responses (Delphi Survey, n = 20)

Source: Authors

Experts recommend establishing a unified governance structure, promoting cross-sectoral collaboration, and leveraging regional programs such as BLUEMED and the Blue Mediterranean Partnership to unlock innovation and funding. Together, these steps could help Egypt overcome systemic barriers and realise its full potential as a regional leader in sustainable blue growth.

3.3.2. Strategic Pillars for Egypt's Circular Blue Economy

In the Egyptian context, expert consensus prioritised three strategic pillars seen as both effective and achievable, given the country's governmental and financial situation: blue financing and investment (90%), circular aquaculture and waste recovery (85%), and sustainable marine and coastal tourism (80%) (Figure 5). These priorities fit well with Egypt's current advantages in aquaculture production, its expanding coastal tourism sector, and its urgent need for varied and climate-friendly funding. The clear expert support for marine-related funding underscores the demand for new ways to finance projects such as sovereign blue bonds and blended finance to solve the ongoing problem of limited funding in marine sustainability and enable major development efforts. Circular aquaculture was viewed as a promising field capable of turning ecological problems into business opportunities, especially in the Nile Delta and Red Sea regions. Meanwhile, coastal tourism, already a key pillar of Egypt's economy, was identified as a practical entry point for applying circular practices through plastic-free zones, eco-certification, and nature-based tourism initiatives.

Conversely, less support for blue energy (45%), marine biotechnology (30%), and digital platforms (25%) reflects Egypt's current challenges in technological readiness, regulatory frameworks, and innovation ecosystems. These sectors, while critical for staying competitive in the future, were perceived as requiring a lot of government help, research funding, and teamwork between agencies before they could grow successfully.

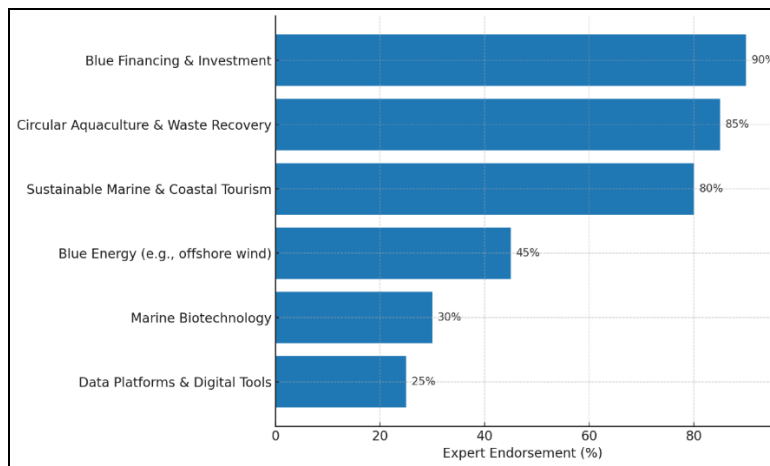


Figure 5. Expert Endorsement of Strategic Pillars for Egypt's Circular Blue Economy (Delphi Survey, n = 20)

Source: Authors

The expert responses suggest a step-by-step plan that fits Egypt's current situation, focusing first on sectors with immediate economic and ecological returns, while preparing the path for future expansion into more advanced blue economy domains. This approach matches the goals in Egypt's national plans, emphasising flexible planning, smart funding, and working with neighbours, particularly within Mediterranean frameworks such as BLUEMED and SwitchMed, to support a just and sustainable transition to a circular blue economy.

3.3.3. Regional Cooperation Mechanisms for Advancing Egypt's Circular Blue Economy

Experts were asked to evaluate the effectiveness of various proposed regional mechanisms to support Egypt's integration into a Mediterranean-wide circular blue economy framework. The most strongly endorsed options were the establishment of a regional consortium or forum (rated highly by 87% of participants) and the development of a joint marine pollution monitoring system (83%). These were followed by shared R&D and innovation funding mechanisms (75%) and regulatory harmonisation across Mediterranean countries (70%) (Figure 6). The findings show that experts clearly prefer institutionalised regional cooperation, particularly through multi-stakeholder platforms and cross-border monitoring systems. The high endorsement of a regional consortium suggests confidence in structured dialogue formats to advance shared goals and streamline initiatives across national boundaries. Similarly, support for a unified pollution monitoring system reflects growing awareness of the transboundary nature of marine degradation and the need for collective environmental stewardship.

These findings show the importance of systems for managing cooperation between countries to enable Egypt to move effectively toward a sustainable marine economy. Experts acknowledge that while national reforms are important, regional consensus offers a multiplier effect, enabling joint funding opportunities, harmonised standards, and coordinated innovation. Strong support for collaborative systems for research and innovation indicates a strong desire for collaborative scientific research and technology development capable of addressing shared challenges, such as marine litter, sustainable fisheries, and blue biotechnology. Meanwhile, agreement on laws and rules, albeit slightly lower, is viewed as a key enabler of applying policies across countries and policy coherence.

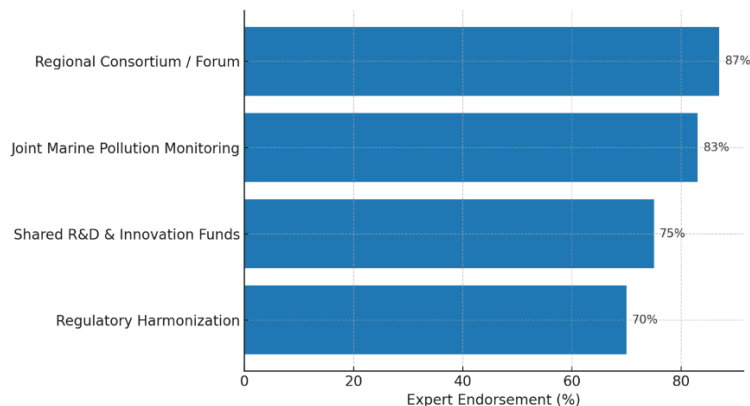


Figure 6. Expert Endorsement of Regional Cooperation Mechanisms for Advancing Egypt's Circular Blue Economy (Delphi Survey, n = 20) Source: Authors

Leveraging platforms such as BlueMed, the Union for the Mediterranean, and the Blue Mediterranean Partnership could therefore provide Egypt with strategic avenues to drive and benefit from regional blue growth, enhancing the protection of nature long-term and economic resilience in the Mediterranean Basin.

3.3.4. Proposed Future Policy Directions for Egypt's Circular Blue Economy

Expert responses identified five connected strategic areas deemed essential for developing a circular blue economy in Egypt. Foremost among these was the development of a comprehensive national strategy that integrates reuse and sustainability concepts across marine and coastal sectors. Such a strategy should promote the use of materials wisely, ecosystem regeneration, and waste minimisation while aligning with Egypt Vision 2030, Sustainable Development Goal 14 (Life Below Water), and key regional frameworks like BLUEMED and Plastic Busters. Experts stressed that this strategy must be supported by an integrated policy framework capable of connecting local and regional plans, fostering synergies across environmental, economic, and different blue economy sectors.

Equally prioritised was the mobilisation of blue finance to fund circular economic infrastructure. Experts advocated for innovative mechanisms such as government-issued green investments and establishing a national blue finance platform to attract investments in areas like marine waste recovery, circular aquaculture, and green ports. Tapping into Mediterranean funding instruments, particularly through the Blue Mediterranean Partnership, was considered very important to unlocking external capital and ensuring project scalability. Strengthening regional cooperation emerged as a key recommendation, emphasising cross-border initiatives for pollution control, plastic reuse, and shared marine resource flows. Experts further proposed the creation of local centres for testing new eco-friendly ideas, especially in cities like Alexandria and Port Said, to pilot circular technologies and promote entrepreneurship in blue sectors. Finally, training institutions and educating the public were seen as essential, encompassing adding these topics to education, giving more responsibility and tools to local governments, and initiatives to inform and engage the public, campaigns to foster behavioural shifts toward sustainable consumption and marine conservation.

Conclusions

The Circular Blue Economy (CBE) represents a paradigm shift in how marine and coastal resources are valued, governed, and utilised. One that is urgently needed to address the environmental, economic, and socio-political challenges facing Egypt and the wider Mediterranean region. By merging the sustainability objectives of the Blue Economy with the resource efficiency and regenerative practices of the Circular Economy, this model offers an integrated framework for achieving inclusive, resilient, and low-carbon development in ocean-based sectors. This shift is beneficial for Egypt, given its extensive coastline, rich biodiversity, and critical role as a regional maritime hub. Despite this potential, the study reveals that Egypt's current engagement with the Circular Blue Economy remains early. Although the country has made notable progress in aquaculture development, port modernisation, and participation in regional initiatives like BLUEMED and the Union for the Mediterranean, its marine economy contributes only marginally (2.2%) to national GDP. This discrepancy highlights a critical disconnect between resource endowment and policy execution. The findings of this research, based on stakeholder mapping, policy gap analysis, and expert insights via a Delphi survey, identify systemic barriers including fragmented institutional frameworks, underdeveloped financing instruments, limited policy coherence, and weak cross-sectoral coordination. Moreover, there is a noticeable absence of an overarching national strategy that formally integrates circularity into marine sectors, impeding both innovation and investment.

However, from this study also surfaces important chances for improvement. Expert consensus underscores high-impact entry points such as circular aquaculture systems, sustainable and regenerative coastal tourism, and the deployment of innovative blue financing tools, including sovereign blue bonds and blended finance models. These areas align not only with Egypt's comparative advantages but also with regional and global sustainability priorities. Equally important is the recognition of regional cooperation as a catalyst for national progress. Experts strongly advocate for Egypt's leadership in establishing transboundary platforms for knowledge exchange, marine pollution monitoring, and harmonised regulatory frameworks, particularly in the face of shared environmental threats such as plastic leakage, biodiversity loss, and climate-induced coastal vulnerabilities. Several strategic imperatives emerge to translate the circular blue economy from a conceptual model into a functioning system. Firstly, Egypt must develop a dedicated National Circular Blue Economy Strategy that includes measurable targets, cross-ministerial implementation plans, and integration with SDG 14 indicators. Secondly, investment in marine innovation hubs, particularly in Alexandria, Port Said, and Red Sea coastal cities, should be prioritised to serve as incubators for eco-entrepreneurship, digitalisation, and community-driven innovation. Third, enabling conditions must be strengthened through capacity building, particularly for local authorities, SMEs, and youth-led initiatives, to democratise access to opportunities in the CBE space.

This transition's success hinges on aligning Egypt's domestic policy architecture with Mediterranean-wide initiatives. Engaging more effectively with programs like SwitchMed and ensuring the full implementation of international legal frameworks (e.g., UNCLOS), will enhance Egypt's visibility and credibility as a regional leader in marine circularity. By doing so, Egypt has the potential to address pressing domestic development challenges such as food security, employment generation, and climate adaptation and shape the future of Mediterranean cooperation based on shared sustainability objectives. Finally, the Circular Blue Economy is not merely a theoretical construct but a strategic development imperative for Egypt. It offers a multi-dimensional opportunity to build ecological resilience, drive inclusive economic growth, and reposition the country as a frontrunner in regional marine governance. However, achieving this vision requires bold policy action, strategic investment, and unwavering commitment to collaboration within Egypt and across the Mediterranean.

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Leonardo PICCINETTI

ORCID ID: <https://orcid.org/0000-0002-7861-5668>

Nahed SALEM

ORCID ID: <https://orcid.org/0000-0003-3536-8502>

Tarek Y. S. KAPIEL

ORCID ID: <https://orcid.org/0000-0002-2213-8911>

Trevor Uyi OMORUYI

ORCID ID: <https://orcid.org/0009-0006-0205-2383>

Alexia Massa GALLUCCI

ORCID ID: <https://orcid.org/0009-0001-4952-9277>

Maghraby Khalil ELSEIFY

ORCID ID: <https://orcid.org/0009-0001-1740-6950>

Alaa A. EL-BARY

ORCID ID: <https://orcid.org/0000-0002-8846-0487>

Mohamed Ramadan A. REZK

ORCID ID: <https://orcid.org/0000-0002-7677-3072>

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TECHNICAL AND ECONOMIC EVALUATION OF PHOTOVOLTAIC PANELS: A CASE STUDY BASED ON INTERDISCIPLINARY APPROACH*

Chaymae Taib ^{1*}, Zineb Aqachmar ²,
Najiba El Amrani El Idrissi ³, Manuela Tvaronaviciene ⁴

^{1,3} Faculty of Science and Technology, Sidi Mohamed Ben Abdellah University, Route d'Imouzzar 30000 Fez, Morocco

^{2*} Faculty of Science, Cadi Ayyad University, Bd Abdelkrim Al Khattabi, 40000 Marrakech, Morocco

⁴ Faculty of Business Management, Vilnius Gediminas Technical University, Saulėtekio al. 11, Vilnius, Lithuania

E-mails: ^{1*}chaymae.taib@usmba.ac.ma (Corresponding author); ²zineb.aqachmar@uca.ac.ma;
³najiba.elamrani@usmba.ac.ma; ⁴manuela.tvaronaviciene@vilniustech.lt

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Abstract. This study evaluates the performance of SoliTek SOLID B.60 bifacial photovoltaic panels in four Lithuanian cities; Vilnius, Klaipėda, Telšiai, and Dotnuva, each representing a distinct climate zone as defined in national classifications. Using the System Advisor Model (SAM) and standardized 2022 weather data from NSRDB, the same technical system and a merchant plant financial model were applied across all cities/ to ensure comparability. Key performance indicators; energy output, capacity factor, levelized cost of energy (LCOE), and Net Present Value (NPV) were analyzed. Results show Klaipėda outperforms other cities in both technical and financial metrics, while Vilnius yielded the lowest performance. The study highlights the advantage of using locally manufactured panels and consistent simulation parameters for realistic assessment. Use of interdisciplinary evaluation approach allows to take into account main technical panels' performance indicators together with economic attractiveness. This approach is especially promising in the context of increasing global competition in the area of photovoltaic industry.

Keywords: photovoltaic; solar energy; performance indicators; System Advisor Model (SAM); climatic zones; interdisciplinary approach; technical evaluation; economic evaluation; Lithuania

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JEL Classifications: O14, O32, O33

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1. Introduction

The global transition towards sustainable energy systems has intensified the focus on photovoltaic (PV) technologies, particularly in regions seeking to optimize local solar potential. In the European context, Lithuania presents a valuable case for PV deployment analysis due to its diverse climatic zones, increasing renewable energy targets, and the presence of local solar manufacturers like SoliTek. Previous research, such as the regional PV performance assessment conducted in Morocco (Aqachmar et al., 2020), demonstrated the importance of evaluating solar installations across varying climate conditions. Inspired by that methodology, this study investigates the performance of the SoliTek SOLID B.60 Bifacial 370W photovoltaic module across four representative Lithuanian cities; Vilnius, Klaipėda, Telšiai, and Dotnuva, each located within a distinct climatic zone identified in Lithuanian climatological studies (Akstinas, 2017).

Using the System Advisor Model (SAM) (*About - System Advisor Model - SAM*, n.d.), a simulation-based software developed by the U.S. National Renewable Energy Laboratory (NREL), we applied a consistent technical configuration and a European merchant plant financial model to assess system viability. By standardizing system parameters and using 2022 Typical Meteorological Year (TMY) data from the NSRDB database (NSRDB, n.d.), this study aims to ensure comparability of results across all locations.

The objective of this paper is to compare photovoltaic performance across Lithuania's key climate zones using real climate data, while emphasizing the benefits of using locally manufactured PV panels. The study also aims to identify the most suitable zones for deployment and provide initial insights for future use of storage systems or net-zero energy solutions

2. Literature review

The deployment and performance assessment of photovoltaic (PV) systems have been widely studied to support renewable energy planning across various climates (Paiano et al., 2023; Tyagi & Kumar, 2024; Zhou et al., 2024)

In Morocco, a study by (Aqachmar et al. 2020) compared PV performance across different climatic regions using simulations to identify optimal zones for solar energy deployment. This approach inspired the current study, emphasizing how geographical and meteorological diversity can affect solar output. The study focused on high-concentration PV plants across six climatic zones in Morocco, demonstrating significant variations in energy yield, capacity factor, and LCOE depending on location. (Ayompe et al. 2010) evaluated the performance of a grid-connected PV system under Irish climate conditions, emphasizing the importance of using accurate local weather data in simulation tools to obtain realistic estimates. Similarly, (Erdinc, Paterakis & Catalaõ 2015) performed a techno-economic analysis of PV systems in different regions of Turkey and identified how regional differences in irradiance and temperature impact the feasibility of solar deployment. Recent studies further highlight diverse PV applications: (Aktas & Ozenc 2024) analyzed the techno-economic and environmental aspects of a grid-connected college rooftop system, (Neama & Alfahed 2024) assessed residential-scale PV in Iraq, and (Zhang et al. 2025) evaluated community-level BIPV systems, showing both aesthetic and environmental benefits. Together, these studies underline how context-specific factors influence the viability and design of PV systems.

Lithuania also shows climate variation across its territory, and (Akstinas, 2017) provided a detailed classification into four climate zones. The System Advisor Model (SAM) by NREL is frequently used in simulation-based PV research. (De Soto et al., 2006) validated models of irradiance and temperature in SAM, while (Blair et al., 2014) offer comprehensive documentation of its technical and financial simulation capabilities. In 2023, (Ayadi et al., 2024) used SAM (version 2023.12.17) to evaluate a 100 MW utility-scale bifacial PV plant in six desert regions, revealing low LCOE and high capacity factors, highlighting SAM's utility across climates. Recent work by (Badran & Dhimish,

2024) also supports bifacial system use in temperate climates, showing 7 to 10% increased energy gain. Another study by (Sun et al., 2018) emphasized that bifacial panels mounted vertically or elevated can significantly increase yield up to 30% depending on albedo and design.

Additionally, the role of locally manufactured PV panels has gained attention for both sustainability and energy security. According to IRENA (IRENA, 2022, 2023, 2025; IRENA Renewable Power Generation Cost, 2020; Renewable Energy Agency, 2024, 2025), localized production can enhance resilience to geopolitical tensions and reduce emissions associated with international logistics. Studies like those by (Kaldellis & Zafirakis, 2011) have also highlighted how using regional manufacturing capacities for renewable technologies strengthens national energy strategies.

3. Methodology

This study adopts a simulation-based approach using the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) to evaluate the performance of photovoltaic systems in different Lithuanian climate zones (see Figure 1). The methodology can be broken down into the following steps:

2.1. Selection of climatic zones and key cities

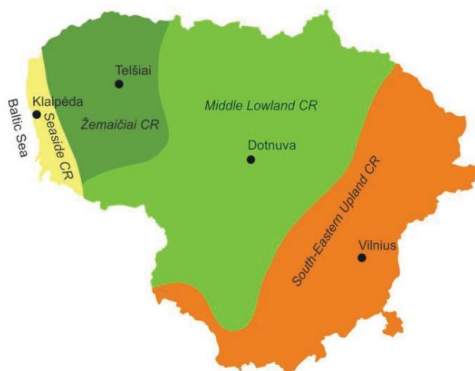


Figure 1. Climate regions of Lithuania and location of meteorological stations
Source: (Akstinas, 2017)

Based on the climatic zone classification proposed by (Akstinas, 2017) this study categorized the country into four principal climatic regions. For each zone, a representative city was selected based on population density and geographical centrality:

- Vilnius (Southeastern zone)
- Dotnuva (Central zone)
- Telšiai (Northwestern zone)
- Klaipėda (Coastal zone)

This zoning enabled a consistent comparative analysis of PV performance across distinct meteorological conditions.

2.2. Weather data acquisition

To ensure consistency and reliability in our simulations, we used Typical Meteorological Year (TMY) 2022 weather data from the National Solar Radiation Database (NSRDB, n.d.) managed by the National Renewable Energy Laboratory (NREL) in the United States. The NSRDB provides hourly weather data with high spatial resolution, based on information collected from satellites and weather stations, which helps maintain a consistent standard across all locations. For each of the four selected cities; Vilnius, Dotnuva, Telšiai, and Klaipėda, the following weather variables were used:

- Global Horizontal Irradiance (GHI) (Reno & Hansen, 2014)
- Direct Normal Irradiance (DNI) (Blanc et al., 2014)
- Ambient temperature
- Wind speed
- Relative humidity

By using data from the same source and selecting the same year for all cities, the approach ensures uniformity in weather inputs, enabling a fair and accurate comparison of PV system performance across different climatic regions.

2.3. PV module selection

The PV panel selected for the simulation was the SOLID B.60 Bifacial 370W by SoliTek, a local manufacturer based in Lithuania. The choice of this module was based on its local production, which aligns with European sustainability goals. Using locally produced panels not only reduces transportation-related emissions but also supports the regional economy. Additionally, the panel utilizes bifacial technology, allowing it to capture sunlight from both the front and rear sides, thereby enhancing system efficiency. This rear-side irradiation capability is particularly beneficial in highly reflective environments, such as those with snow-covered surfaces.

The module specifications were manually entered into SAM (System Advisor Model) based on its datasheet (Bifacial, n.d.). It has a nominal maximum power output of 370 W, with an efficiency of approximately 20%. The temperature coefficient is $-0.32\ \%/^{\circ}\text{C}$, indicating the power loss with increasing temperature. The open circuit voltage (V_{oc}) is 40.50 V, and the short circuit current (I_{sc}) is 11.18 A. Under maximum power conditions, the panel operates at a voltage (V_{mpp}) of 34.86 V and a current (I_{mpp}) of 10.62 A. The panel uses bifacial cells (Guerrero-Lemus et al., 2016) and a glass-glass structure, which means it's made with glass on both sides to make it more efficient and durable.

2.4. PV system configuration in SAM

All simulations were conducted using System Advisor Model (SAM) version 2024.12.12. The system was configured using the "Photovoltaic → Detailed PV → Merchant Plant" model. This option was chosen because it allows for detailed technical and financial modeling of grid-connected PV systems, with flexible inputs options.

The configuration was based on the SOLID B.60 Bifacial 370W module and optimized for Lithuania's climate. To maintain consistency across all simulation sites, the following setup was used: 900 modules arranged as 30 modules per string with 30 strings in parallel resulting in a total DC capacity of 333.2 kW_{dc} ($900 \times 370\text{ W}$). The ground coverage ratio (GCR) was set to 0.45, ensuring realistic row spacing, as supported by (Ferry et al., 2025) for European installations. The modules were installed at a ground clearance of 1.5 meters. A fixed tilt angle of 30° was chosen to match Lithuania's latitude ($\sim 55^{\circ}$) (*GPS Coordinates of Lithuania. Latitude: 55.1736 Longitude: 23.8948*, n.d.) following the common practice in countries with climates similar to Lithuania, such as Poland (*What Is the Optimal Solar Panel Tilt Angle? Poland and the World - Electrum*, n.d.). The azimuth angle was set to 180° , meaning the panels were facing south to maximize solar exposure. The fixed tilt system was selected instead of a tracking system to reflect a cost-effective and low-maintenance solution, commonly used in Lithuania and similar climates (IRENA Renewable Power Generation Cost, 2020).

The economic configuration was based on the Merchant Plant model, where the plant sells electricity directly to the market. Financial estimates commonly used in Europe were applied, with an electricity sale price of 110 €/MWh as the market average, operation and maintenance costs set at 20 €/kW/year based on regional averages (IRENA Renewable Power Generation Cost, 2020), a discount rate of 6%, an inflation rate of 2%, and a project lifetime of 25 years. The financial model excludes subsidies and tax incentives to maintain a conservative and broadly applicable scenario.

2.5. Performance indicators

To assess and compare the performance of photovoltaic systems across Lithuania's climate zones, four key performance indicators (KPIs) were selected. These indicators capture both the technical performance and economic feasibility of each simulated PV installation.

Annual energy yield (AEY)

The annual energy yield is the total amount of electrical energy generated by the PV system over a year under real-world conditions. It is expressed in kilowatt-hours (kWh).

Capacity Factor (CF)

The capacity factor (%) is the ratio of actual electricity generated over a period of time to the energy that would have been generated if the plant operated at full capacity during that time. A higher capacity factor indicates better system utilization.

Levelized Cost of Energy (LCOE)

LCOE (€/kWh) represents the average cost per unit of electricity generated, accounting for the total lifecycle costs (investment, operations, and maintenance) and electricity output (IRENA Renewable Power Generation Cost, 2020). A lower LCOE suggests a more economically attractive system.

Net Present Value (NPV)

NPV (€) evaluates the financial profitability of a project by comparing the present value of cash inflows to outflows over its lifetime. A positive NPV indicates that the project is financially viable.

These KPIs allow for a comparison of PV installations across cities, capturing both the energy efficiency (via the AEY and CF) and economic performance (via LCOE and NPV). By integrating these indicators, decision makers can better evaluate the suitability of PV projects under different climatic and financial conditions.

3. Results and discussion

This section presents and discusses the simulation results of the SOLID B.60 bifacial PV system deployed across four representative cities of Lithuania: Vilnius, Dotnuva, Telšiai, and Klaipėda. The analysis is centered on the technical performance, economic feasibility, and energy generation dynamics, drawing comparisons across regions using key performance indicators: Annual Energy Yield, Capacity Factor, Levelized Cost of Energy (LCOE), and Net Present Value (NPV).

3.1. Annual energy yield

The annual AC energy yield represents the total electricity delivered to the grid during the first operational year.

Table 1. Comparison of annual AC energy, energy yield, and performance ratio across the four cities

City	Annual AC energy (kwh)	Energy yield (kwh/kw)	Performance ratio
Vilnius	279,391	839	0.76
Dotnuva	291,555	875	0.76
Telšiai	286,451	860	0.75
Klaipėda	306,235	919	0.74

As shown in Table 1 above, Klaipėda achieved the highest energy production of approximately 306,235 kWh, followed by Dotnuva (291,555 kWh) and Telšiai (286,451 kWh). Vilnius had the lowest yield at 279,391 kWh. This result is consistent with Klaipėda's location in the coastal region, which benefits from higher solar irradiation and fewer extreme cold spells, enhancing photovoltaic conversion. In contrast, Vilnius, located inland with more

cloud cover and colder winters, recorded the lowest output, despite sharing the same PV configuration, highlighting the climatic variability across regions.

Performance ratios across all cities hovered between 0.74 and 0.76, indicating relatively stable system losses (e.g., from temperature, inverter inefficiencies, or soiling), with no region-specific anomalies. This supports the robustness of the bifacial module and system design across Lithuania's climatic diversity.

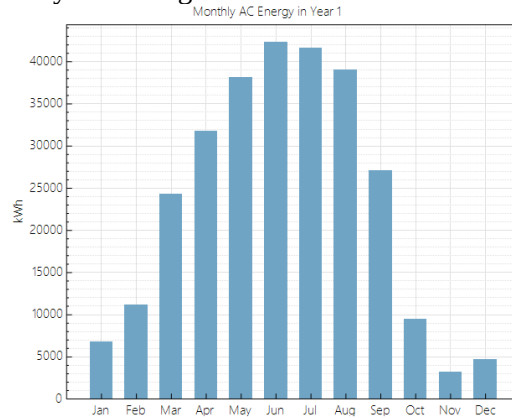


Figure 2. Monthly distribution of AC energy generation in year 1 - Vilnius

Figure 2 above illustrates the monthly AC energy production of the Vilnius installation during the first year. Peak generation occurs in June and July, while November shows the lowest output due to reduced irradiance and shorter daylight hours.

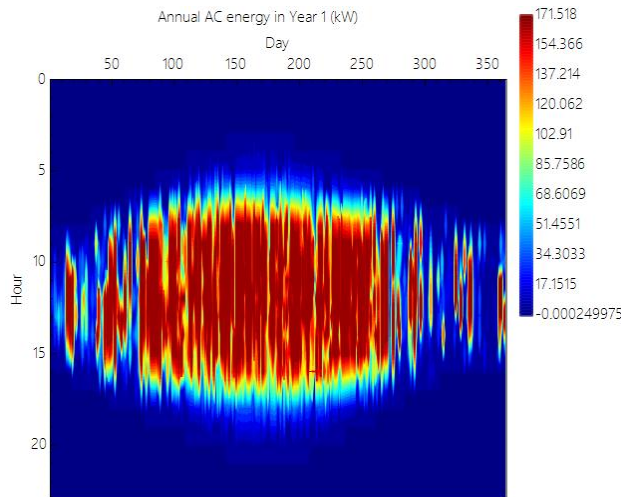


Figure 3. Annual hourly AC energy generation heatmap - Vilnius

The heatmap (Figure 3) reveals a pronounced concentration of energy production between 9:00 and 16:00 from April to August. The seasonal patterns align with expected solar availability in southeastern Lithuania.

Similarly, the central region city of Dotnuva exhibits a comparable but slightly reduced generation profile (see Figure 4 below).

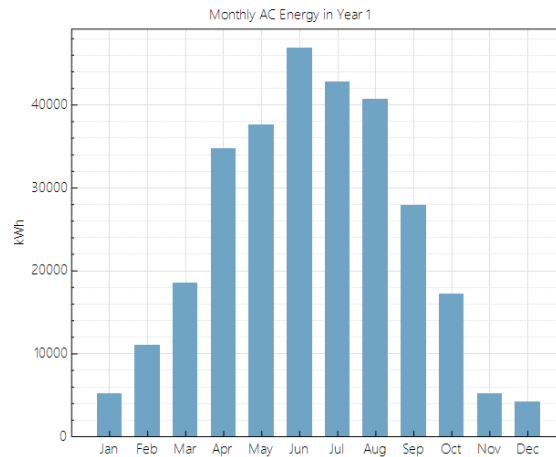


Figure 4. Monthly distribution of AC energy generation in year 1 - Dotnuva

Dotnuva's monthly production shows a similar seasonal pattern, with the highest output during summer months and a noticeable dip in winter. Overall, the energy yield remains relatively stable during spring and fall (Figure 5).

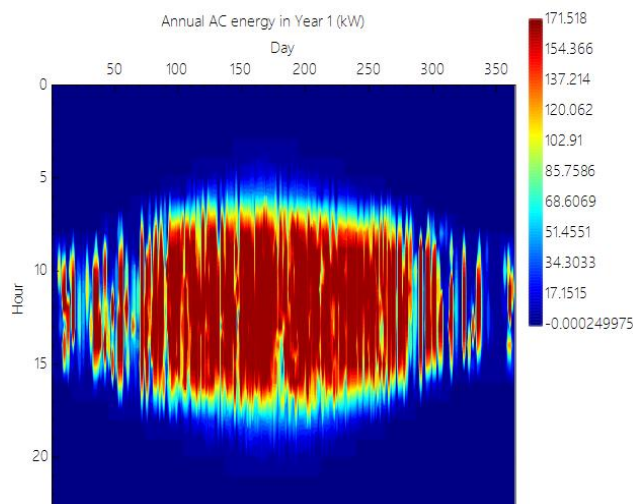


Figure 5. Annual hourly AC energy generation heatmap - Dotnuva

The heatmap for Dotnuva confirms steady performance during midday hours in summer, with a gradual ramp-up and decline around the peak months. Winter months show significantly limited energy production.

In the northwestern region, Telšiai's energy profile is influenced by slightly lower irradiance and cooler temperatures (see Figure 6 below).

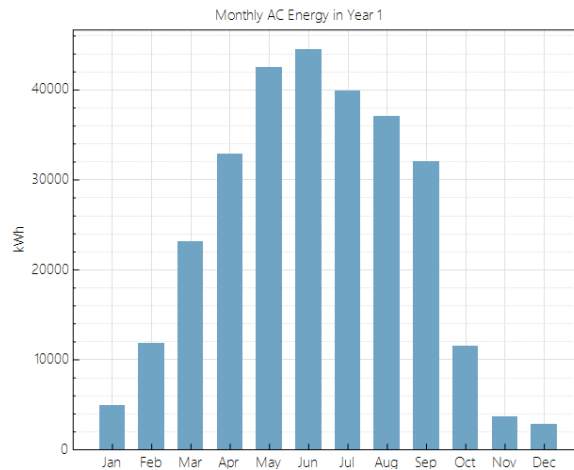


Figure 6. Monthly distribution of AC energy generation in year 1 - Telšiai

Monthly AC energy production in Telšiai mirrors the general seasonal pattern but with slightly lower summer peaks compared to Vilnius and Dotnuva (Figure 7). The winter production remains minimal, reflecting regional solar availability.

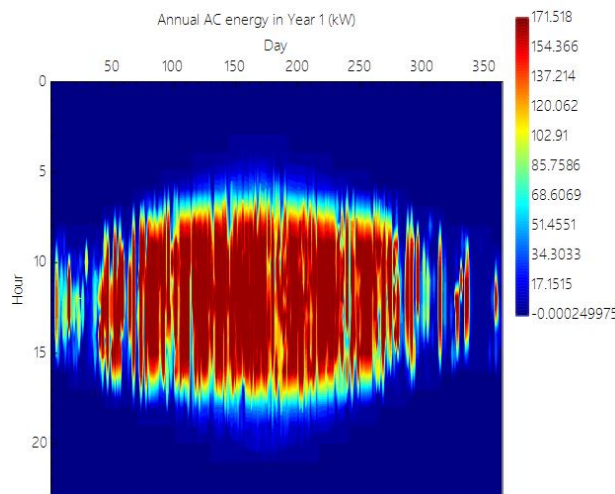


Figure 7. Annual hourly AC energy generation heatmap – Telšiai

The heatmap highlights consistent summer performance with limited variability, though daily generation appears slightly compressed compared to southern counterparts, possibly due to cloud cover or diffuse irradiance conditions.

Finally, Klaipėda, representing the coastal region, shows a distinct generation pattern due to maritime influence (Figure 8).

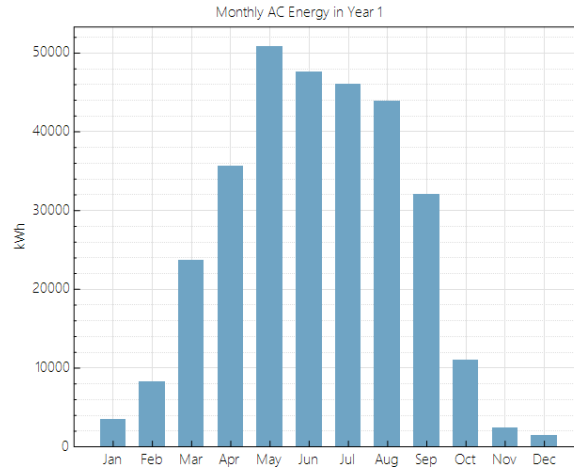


Figure 8. Monthly distribution of AC energy generation in year 1 - Klaipėda

Klaipėda's monthly energy yield demonstrates smoother transitions between months, with less pronounced seasonal extremes. This stability may be attributed to the moderating effects of the coastal climate.

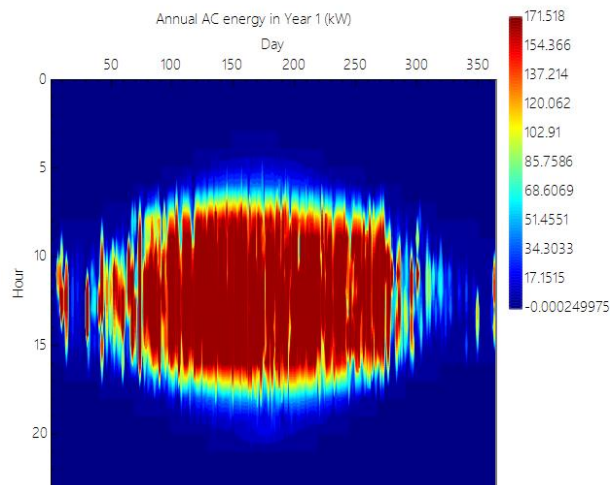


Figure 9. Annual hourly AC energy generation heatmap - Klaipėda

The generation heatmap for Klaipėda (Figure 9 above) reveals sustained midday production throughout much of the year, with slightly fewer sharp peaks compared to inland cities, indicating more diffuse radiation and consistent weather patterns.

3.2. Capacity factor

The DC capacity factor indicates how effectively each system operates compared to its maximum potential, showed slight regional variation in Table 2.

Table 2. DC capacity factor of the PV system across different climatic zones of Lithuania

City	Capacity Factor (%)
Klaipėda	10.5
Dotnuva	10.0
Telšiai	9.8
Vilnius	9.6

Although values are relatively close, Klaipėda again led with the highest capacity factor, exceeding the 10% threshold, suggesting more favorable solar irradiance. The difference percentage points between Klaipėda and Vilnius is significant, especially in long-term energy projections. This confirms that location-specific solar availability directly impacts system effectiveness, even in a country with overall moderate solar resources.

3.3 Levelized Cost of Energy (LCOE)

The LCOE, representing the average cost of electricity produced over the system's lifetime, incorporates capital, O&M, and financial assumptions. Both nominal and real values are shown in Table 3 and Table 4 respectively.

Table 3. Levelized cost of energy (LCOE) - nominal - in Vilnius, Dotnuva, Telšiai, and Klaipėda

City	LCOE nominal (€/kWh)
Klaipėda	11.47
Dotnuva	11.90
Telšiai	12.05
Vilnius	12.28

Table 4. Levelized cost of energy (LCOE) - real - in Vilnius, Dotnuva, Telšiai, and Klaipėda

City	LCOE real (€/kWh)
Klaipėda	9.29
Dotnuva	9.64
Telšiai	9.76
Vilnius	9.95

Again, Klaipėda stands out with the lowest LCOE, demonstrating higher economic efficiency. This is driven mainly by its superior energy yield, which spreads the investment and operational costs over more kilowatt-hours, thereby reducing the average cost per unit. The financial benefit becomes more evident when combined with the net present value.

3.4. Net Present Value (NPV)

NPV evaluates the overall profitability of the system by taking into account future cash flows discounted over time.

Table 5. Financial Profitability Metrics: Net Present Value (NPV)

City	NPV (\$)
Vilnius	64,204
Dotnuva	86,038
Telšiai	78,432
Klaipėda	102,768

The NPV results clearly highlight that Klaipėda is the most profitable location for PV deployment in Lithuania (see Table 5 above). Dotnuva follows closely, suggesting that central regions may also offer economically viable opportunities for solar projects. Vilnius, despite being a major urban center, yielded the lowest NPV due to its relatively lower energy yield.

Interpretation

Klaipėda shows the most favorable combination of technical and financial performance. Its coastal conditions, higher irradiance, and fewer extreme winters result in better PV system efficiency and lower costs. Dotnuva and Telsiai perform well technically and economically, supporting the idea that central and northwestern regions are suitable for solar deployment. Vilnius, while showing the lowest figures, still meets acceptable performance standards, confirming the nationwide viability of PV technology.

Conclusions

This study evaluated the performance of a locally produced bifacial photovoltaic module across four representative Lithuanian cities; Vilnius, Dotnuva, Telsiai, and Klaipėda, each corresponding to a distinct climatic zone. Using the system advisor model (SAM) and standardized TMY weather data from the NSRDB, we conducted a uniform simulation and financial analysis to assess key performance indicators, including annual energy yield, capacity factor, LCOE, and NPV.

The results show that although Lithuania has a relatively homogenous climate, regional variations affect photovoltaic performance. Klaipėda demonstrated slightly higher energy outputs and financial returns, attributed to better irradiation and lower system losses. Despite these differences, all zones exhibited strong potential for PV deployment, particularly with the SoliTek SOLID B.60 bifacial module, which proved well-adapted to local conditions.

These findings highlight the value of regionalized energy planning and emphasize the importance of using locally manufactured modules in Lithuania's PV strategies. Beyond the Lithuanian context, this research framework can be adapted to evaluate alternative PV technologies under the same climatic and financial scenarios. Doing so would provide valuable comparative insights for policymakers, investors, and researchers, supporting broader decision-making on optimal technology selection for renewable energy projects across Europe and similar climates.

Limitations and future work

While this study provides valuable insights into the performance of photovoltaic systems across Lithuania's climate zones, several limitations should be acknowledged.

Single module type and fixed tilt configuration: The analysis focused exclusively on one module model (SoliTek SOLID B.60 Bifacial 370W) and a fixed tilt system set at 30°. While this approach ensured uniformity, it excluded alternative technologies (e.g., monofacial (Matarneh, Al-Rawajfeh & Gomaa, 2022), thin-film (Ebner et al., 2015; Lee & Ebong, 2017)) or configurations (e.g., tracking systems (Amelia et al., 2020; Hafez et al., 2018)) that may perform differently under the same climatic conditions.

Use of simulated data only: This study used typical meteorological year (TMY) data from the NSRDB, which represents long-term average weather patterns but does not capture real-time variations. Consequently, short-term climatic events such as snow or temporary shading from vegetation were not included in the analysis. These omissions may lead to differences between simulated results and actual photovoltaic system performance in real conditions.

Static economic assumptions: Economic modeling was based on constant electricity sale prices, discount rates, and O&M costs. However, these variables are likely to evolve due to market dynamics, inflation, policy changes, and technological advancements.

Future research could enhance the current analysis by incorporating several additional dimensions. First, deploying experimental PV installations across the studied regions would provide real-world data to validate and refine simulation outcomes. Second, testing a wider range of photovoltaic technologies, such as monofacial or thin-film panels, would allow a broader performance comparison under uniform conditions. Third, incorporating optimization techniques for panel orientation, tilt, and tracking systems could improve energy yield estimates. Moreover, integrating storage solutions would enable modeling of self-consumption patterns and energy autonomy. Finally, simulating various economic and regulatory scenarios, such as fluctuating electricity prices or policy incentives, would offer a more robust framework for long-term investment and planning.

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Author Contributions: Conceptualization: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*; methodology: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*; data analysis: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*, writing—original draft preparation: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*, writing; review and editing: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*; visualization: *Chaymae Taib, Zineb Aqachmar, Najiba El Amrani El Idrissi, Manuela Tvaronaviciene*. All authors have read and agreed to the published version of the manuscript.

Chaymae TAIB Ph.D. student and software engineer specialized in embedded systems with professional experience in the automotive industry. She graduated from ENSA Fès, Morocco, with a degree in embedded systems and industrial computing. Her research interests include applying artificial intelligence in healthcare and exploring innovative digital technologies.

ORCID ID: <https://orcid.org/0009-0003-3060-8367>

Zineb AQACHMAR engineer and associate professor-researcher at the faculty of sciences Semlalia, Cadi Ayyad university (Marrakech, Morocco). She holds an engineering degree from ENSEEIHT, Toulouse (France) and completed her Ph.D. at USMBA (Morocco) in the field of solar energy. Her research focuses on photovoltaic technologies, particularly the energy, economic, and environmental assessment of solar systems (CSP, CPV) and their applications in Morocco and Africa.

ORCID ID: <https://orcid.org/0000-0003-4412-5596>

Najiba EL AMRANI EL IDRISSE is a full professor of electrical engineering at the faculty of sciences and techniques, Sidi Mohamed Ben Abdellah university, Fez, Morocco. She holds a Ph.D. in electrical engineering and is a senior member of the signals, telecommunications, and smart electrical networks research team within the signals, systems, and components laboratory. She has coordinated and participated in several EU-funded research projects under FP6, FP7, Horizon 2020, and Erasmus+.

ORCID ID: <https://orcid.org/0000-0001-5603-1306>

Manuela TVARONAVICIENE is a professor at Vilnius Gediminas Technical university (Lithuania). Her research interests cover sustainable development, innovation, foreign direct investment, entrepreneurship, energy security and regional economic growth.

ORCID ID: <https://orcid.org/0000-0002-9667-3730>

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INDIGENOUS KNOWLEDGE FOR SUSTAINABLE AGRICULTURE DEVELOPMENT: BANANA RIPENING METHODOLOGIES FROM SOUTH AFRICA*

Beata Kilonzo ¹, John B. Ochanda Ogola ², Ishmael Obaeko Iwara ^{3*}

^{1,2,3*}University of Venda, P/Bag X5050, Thohoyandou, South Africa

E-mails: ¹beata.kilonzo@univen.ac.za; ²ochanda.ogola@univen.ac.za;
^{3*}ishmael.iwara@univen.ac.za (Corresponding author)

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Abstract. In South Africa, where bananas are produced commercially, small-scale farmers have traditionally used various Indigenous technologies to speed up the ripening process of the fruit. This vital Indigenous knowledge system greatly enhances food security, entrepreneurship, and sustainable livelihoods. However, the documentation of these processes is scarce in the scientific literature, risking their extinction. This study adopts a qualitative case study approach, using purposive and snowball sampling techniques to profile the technologies from key knowledge holders in Limpopo and Mpumalanga Provinces. The findings highlight the diverse and effective nature of these traditional practices, which utilise natural materials such as ashes, cow dung, chicken manure, local chambers, maize byproducts, and Indigenous leaves like Musudzungwane or Mugwiti. The motivation to sustain these Indigenous techniques includes their availability, accessibility, cost-effectiveness, and eco-friendliness. This research contributes to a broader understanding of Indigenous agricultural practices and emphasises the importance of continued documentation and integration of traditional knowledge within modern frameworks. Developing educational programmes aimed at transferring Indigenous knowledge to younger generations could help preserve and sustain this vital cultural heritage and improve the livelihoods of small-scale farmers.

Keywords: African Indigenous knowledge; agri-entrepreneurship; banana ripening; food security; rural development

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JEL Classifications: Q13

1. Introduction

Globally, Indigenous knowledge systems play a vital role in local development (Madonsela, Semanya & Shale, 2024; Stanly et al., 2024; Kom, Nicolau & Nenwiini, 2024). It offers sustainable, context-specific and locally adapted solutions rooted in centuries of rich knowledge and experience. From business, technology, and traditional farming techniques that preserve biodiversity to community-based resource management systems, Indigenous practices frequently align with ecological balance, environmental stewardship and long-term resilience (Olaniyan & Govender, 2023; Melash et al., 2023; Mbelebele et al., 2024; Dorji et al., 2024; Gebremichael, Didanna & Ayza, 2025; Fa & Luiselli, 2025). In regions affected by climate change, economic underdevelopment, food insecurity, poverty, and environmental degradation, integrating Indigenous knowledge and wisdom into development strategies can drive innovation, empower marginalised individuals and

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communities, and ensure that growth and development are inclusive and culturally respectful. Recognising and valuing this knowledge system is not only ethical but also economically strategic and viable.

The ripening of bananas, an essential process for their consumption and commercialisation, has historically been supported by various Indigenous techniques across Africa (Ajayi & Mbah, 2007; Sogo-Temi, Idowu & Idowu, 2014; Bantayehu & Alemayehu, 2020). Deeply rooted in cultural practices, these methods have been vital for small-scale farmers who rely on bananas as a staple crop and economic resource. Farmers in South Africa, a country producing bananas in significant commercial amounts, especially in rural areas like Mpumalanga and Limpopo, have developed Indigenous traditional ripening techniques that reflect their deep understanding of local environmental conditions and agroecological practices. These essential localised traditional methods, which have existed for centuries and are passed down orally through generations, are uniquely adapted to the resources available and serve as an alternative to costly modern banana ripening technologies. Despite their importance, however, these practices remain largely undocumented in scientific literature, leaving a conspicuous gap in understanding their contribution to sustainable agriculture and food security in South Africa and beyond.

The lack of scientific documentation of Indigenous banana ripening technologies in South Africa poses a significant threat to their conservation and development. This is because oral knowledge transmission, which historically was the primary avenue of passing on this essential Indigenous technique, is increasingly at risk due to shifting cultural dynamics and the ageing of knowledge custodians. As globalisation emerges, technology advances and communities modernise, thus influencing behaviours and practices (Balogun, Aruoture & Haruna, 2024; Tughhemba & Peter, 2024). Consequently, younger generations adopt new technologies, shifting from the initial African traditional oral-based typologies of knowledge dissemination and assimilation to conventional Western-oriented approaches. As a result, the rich heritage of Indigenous agricultural practices, such as Indigenous banana ripening methods, risks becoming obsolete.

The above argument on cultural dynamics and globalisation finds legitimacy in Akinola, Pereira, Mabhaudhi, Bruin and Rusch (2020), who maintain that Indigenous knowledge systems are frequently undervalued in contemporary research despite their potential to provide sustainable and context-specific solutions to challenges such as food insecurity and climate change. This worrying conception leaves a narrative that, without intentional efforts to adequately document, analyse, and integrate these Indigenous practices into modern agricultural frameworks, the vital knowledge may become extinct, depriving future generations of insights that could enhance resilience and innovation not only in banana farming but broader agrarian practices.

Substantiating the earlier advanced standpoints, profiling these Indigenous knowledge systems is not only a matter of conservation but also an essential step towards their improvement and potential integration with modern agricultural practices. In the current era of globalisation, no knowledge, skills or techniques exist in isolation; hence, every unique trait practised in silos must be recognised and integrated into the global landscape. Besides, like any technology, understanding traditional methods for banana ripening and principles is key to optimising their efficiency, scalability and efficacy. This process can also reveal opportunities to adapt these techniques to contemporary challenges, such as reducing post-harvest losses or enhancing the nutritional value of bananas. This is evident in Sekhar, Rastogi, Saikanth, Rout, Kumar and Patel (2024), who suggest that blending Indigenous knowledge systems with modern science will lead to innovative solutions that are both sustainable and culturally relevant to societies. Against these arguments, this study aims to bridge the critical knowledge gap by systematically profiling and analysing Indigenous banana ripening technologies traditionally used in rural areas of South Africa. It is believed that such efforts will contribute to their conservation, advancement, and potential integration into the broader web of agricultural practices.

2. Global Overview of Banana Ripening Techniques

Banana ripening is a crucial process that influences the fruit's taste, quality, and marketability. Globally, many modern and traditional ripening techniques are utilised, reflecting cultural practices, regional resources, and technological advancements (Saranya et al., 2023; Laryea et al., 2025).

For instance, in Europe and North America, large-scale commercial ripening facilities use advanced modern ripening techniques such as ethylene gas chambers to ensure uniform ripening. These chambers maintain optimal temperature and humidity levels, allowing banana fruits to ripen uniformly during transit and storage before reaching end-point outlets like supermarkets (Paull & Chen, 2021). In Australia, similar advanced modern techniques are frequently employed to cater to domestic markets, where consumers demand visually appealing and high-quality banana fruits. Interestingly, countries like Japan have also adopted innovative techniques, including ripening banana fruits under controlled oxygen-depleted environments to enhance shelf life and appealing tastes - sweetness (Srilaong & Tatsumi, 2002). These advanced methods conform to global market demands and highlight the shift toward mechanisation and precision in agricultural practices. While conventional methods offer consistency and quality control, traditional ripening techniques, especially Indigenous techniques, are still widely used in developing regions and emphasise the importance of cultural conservation and resource optimisation.

A similar trend was observed in South Asia, particularly in India and Bangladesh, where ethylene gas from kerosene lamps and small coal-fired chambers is traditionally utilised to hasten the ripening of banana fruits (Islam et al., 2016; Zore et al., 2021). Parallel to the former, in parts of Latin America, including countries such as Colombia and Ecuador —major banana exporters—banana fruits are ripened in controlled environments using techniques like ethylene gas chambers (Ruiz Medina & Ruales, 2024). These chambers allow for symmetrical ripening and precise control over temperature and humidity, ensuring the ripened fruits meet international quality standards. This technique, although effective, has ripple effects, especially health and environmental concerns, due to its inherent potentially hazardous materials. Some artificial mechanised ripening techniques that rely on chemical agents can lead to alterations in the active components of banana fruits, potentially causing physiological issues in human beings (Chandar & Smith, 2019). For instance, chemicals such as calcium chloride, calcium carbide, ethephon, and ethylene glycol frequently utilised in the banana ripening process, have potential health hazards (Chandar & Smith, 2019), emphasising the need for prioritising natural or less harmful ripening techniques to ensure food safety. Natural banana fruit ripening techniques provide the most beneficial effects without posing toxicity risks to health, making them safer for consumption.

In ancient Sri Lanka, natural techniques involving smoking were a traditional and efficacious approach to ripening bananas, achieving nearly 100% success (Ranaweera, Ampemohotti & Arachchige, 2020). Smoke is generated by burning semi-dried leaves and directed into the pit to sulphonate the banana fruits, thus accelerating their ripening process naturally (Maduwanthi & Marapana, 2019). This method leverages heat and ethylene production from the smoke to enhance ripening and achieve the desired results. The smoking process increased the temperature conditions around the banana fruits, which stimulated the production of ethylene - a natural hormone responsible for ripening the fruits. Storing banana fruits at this elevated temperature expedited the natural ripening process, resulting in softened, swift ripened process. Like most other natural methods, this technique allowed for the acceleration of banana ripening without the use of harmful chemicals, making it not only safe for human consumption but also an eco-friendly technique. However, this technique's ripening process was somewhat complex, resulting from deficiencies in advanced tools, skills and technical knowledge at the time, thus leading to its gradual underutilisation.

Raw agricultural wastes, such as wheat grain and rice straws, were another documented natural harnessed ripened banana fruits techniques in traditional agricultural practices in Asia (Chandar & Smith, 2019). The process

involves placing the bananas in a confined space, layered with the materials. These organic materials are active in creating a warm and humid environment in the space, which accelerates the fruit ripening process by trapping ethylene gas - a natural plant hormone released by banana fruits that enhances ripening. The insulation provided by the straw or sawdust facilitates even heat distribution in the environment and minimises moisture loss, resulting in a uniformly ripened process with enhanced flavour and texture. A notable implication of this technique is that it is both cost-effective and eco-friendly, making it a sustainable alternative to artificial mechanised ripening agents frequently used. These Indigenous methods are valued for their simplicity and cost-effectiveness, particularly in rural areas where access to modern ripening technologies is limited. It also reflects the deep-rooted Indigenous knowledge of local communities in leveraging available resources and local practices for agricultural processes. However, the lack of standardised processes for these Indigenous methods frequently results in inconsistent ripening processes, ultimately affecting small-scale farmers' marketability and income.

3. Methodology

This study was conducted in the Limpopo and Mpumalanga Provinces in South Africa. The choice of location hinges on tremendous banana production and marketing endeavours in the area compared to other provinces. An exploratory qualitative case study research methodology was employed, utilising a participatory community-led action research approach. This approach aimed to identify the Indigenous techniques for ripening banana fruits in the areas and the motivation for the practices. The essence of participatory action research hinges on the need to facilitate robust engagements with grassroots knowledge holders to profile the banana species, enabling knowledge conservation and transfer.

Essential knowledge holders were purposively sampled through key informants and research assistants to engage in the study. This sampling technique was ideal for identifying well-endowed knowledge holders with extended experience in banana production in the study area. Subsequently, more participants were snowballed into the circle until the saturation threshold was reached, that is, a point where information gathered from additional members on the subject matter was insignificant to the former. At this point, 144 participants had been engaged through a focus group physical contact discussion of 9 members each, using a semi-structured questionnaire. In all, 16 focus group discussions were held. Five grassroots farmers with advanced experience and knowledge of banana production in the locale were interviewed using a one-on-one technique, bringing the total number of participants to 149. This data collection engagement spans from May 2022 to June 2023, aside from inception preparations and community entry arrangements that were not reported. The collected data excerpts were then transcribed into 21 documents (D) in line with the focus groups and input into the Atlas-ti v8 software for analysis, utilising an open coding system for sentiment analysis. This facilitated the organisation and modelling of the data to identify key contents and patterns related to the banana species and farmers' rationale for venturing into them.

4. Findings

Seven banana-ripening Indigenous techniques emerged from the analysis. As illustrated in Table 1, this includes Ash, Tree leaves, Local Chamber, Animal Faeces, Maize byproducts, Tree leaves, and Fruits. The adoption and conservation of these techniques from one generation to another hinges on their cost-effectiveness, availability of agents, natural ripening process, and original taste retention.

Table 1. Banana fruit Indigenous ripening technique in Limpopo and Mpumalanga

Technique	Motivation	Process	Timeframe	Limpopo	Mpumalanga
Ash 	Affordable Availability Fast ripening	The banana is covered with ashes and sealed with a sack to absorb heat. It takes a maximum of one week to reach the expected ripened threshold.	7 days	X	
Tree leaves 	Affordable Availability Fast ripening Natural taste Yellow color	The harvested banana fruit is split evenly and sealed in sack bags or wrapped in blankets alongside tree leaves called Musudzungwane. To ripen, it is stored in confined spaces, like Nkho – clay pots, calabash, iron pots, bins, trunks, drums, and ground holes.	5-9 days	X	X
Local Chamber 	Affordable Availability Fast ripening Healthy Long shelf life Natural taste	A bunch of bananas are stored in Dulu, a confined structure made of wood, mud, and stones with grass roofing.	days	X	X
Animal Faeces 	Eco-friendly Fast ripening	Split banana bunches are wrapped with newspapers and sealed in a sack bag alongside chicken manure or cow dung to ripen my bananas.	7days	X	
Maize byproduct 	Affordable Eco-friendly Organic Natural taste	The banana bunch is split evenly and sealed in a sack alongside Mufumbu - coarse residue from maize powder.	1-2 weeks	X	
Tree leaves 	Affordable Available Eco-friendly Natural taste Organic	Mugwiti Indigenous tree leaves are positioned between bunches of bananas, packed in a sack.	7 days	X	
Fruits 	Affordable Available Eco-friendly Natural taste Organic	The banana fruits, combined with granadilla fruits or ripe banana peels, are either sealed in a sack bag or put in a container and covered with boxes.	7 days	x	x

Source: Authors' consolidation based on primary data

4.1. Ash technique

In many rural areas of Africa, traditional agricultural practices are not just a means of cultivation, but a reflection of deep-rooted Indigenous knowledge passed down through generations. These practices, frequently overlooked in modern agricultural discourse, provide insights into sustainable farming techniques that have stood the test of time. In Limpopo and Mpumalanga provinces, small-scale entrepreneurs utilise a unique and time-honoured method to ripen banana fruits, a staple food crop in South Africa. The expression below captures the detailed

ripening process shared by one of the local farmers who participated in this study, emphasising the significance of Indigenous African banana ripening techniques in maintaining food security and cultural heritage.

"When I ripen the banana, I use ashes. I cover the banana with ashes and put it in a sack to absorb heat. Then, the sack is tied very tightly so that no air penetrates. After a week or so, the banana is ripe and ready to be eaten. This process typically takes a week for the banana fruits to ripen evenly and be ready for either household consumption or sale."

As explained by one of the knowledge holders, this practice reflects a process rooted in a profound understanding of local environmental conditions. Using ashes, the banana fruit entrepreneur ensures heat retention and prevents air from interfering with ripening. The tightly tied sack creates an atmosphere conducive to the uniform ripening of the banana fruit, showcasing a low-cost and resource-efficient technique that leverages locally available materials. Ashes, a byproduct of wood or plant material combustion, are teeming and accessible in these rural settings, as many rely on traditional fire cooking methods. The ashes serve a dual purpose: 1) heat retention, which accelerates the ripening process, and 2) creating a semi-sealed environment that limits the exposure of the fruit to oxygen, thus controlling the rate of ripening. Similarly, sealing the bananas in a sack minimises the external variables like humidity and air circulation that could affect the ripening process. This method is particularly effective in ensuring that the fruits ripen evenly without the risk of them spoiling prematurely.

4.2. Tree leaves

The technique described is one of several Indigenous methods frequently utilised in the local areas to ripen bananas. Another stakeholder sheds light on one such traditional method involving using a clay pot, known as Nkho, and a variety of Indigenous tree leaves to ripen bananas, offering insight into the ingenuity and resourcefulness of local farmers. The process involved in this technique begins with carefully harvesting bananas and dividing the large bunches into manageable portions. In the past, clay pots were frequently used for this technique; however, the disappearance of some traditional practices, which made the pots scarce, resulted in the adaptation of alternate means such as metal drums, bin containers and boxes. Despite this shift, the essence of the ripening process remains rooted in Indigenous knowledge, particularly the use of Indigenous leaves. When placed in a confined space like clay pots, these leaves release heat, creating a microenvironment within the box that accelerates the ripening process.

"Long back, we used a clay pot named Nkho or a box and even bin containers to ripen the bananas. When the bananas have grown big and are ready for harvest, we would cut the bunch from the tree. We would divide the bananas from the bunch, steam and put them inside the clay pot. Furthermore, we would cut a traditional tree named musudzungwane put the leaves on top of the bananas and close it for ripening. When it gets ready after 5 days, it will be very appealing with a nice yellow colour. The banana does not release sweat or water when it is ripened using Nkho and Indigenous tree leaves."

In this traditional method, the clay pot, Nkho, is crucial in creating the ideal microenvironment for ripening bananas. The pot's material allows for a stable, insulated environment that regulates temperature and humidity, crucial factors in the ripening process. The choice of musudzungwane leaves is equally significant, as they likely possess properties that either aid in the ripening process or prevent the bananas from sweating or releasing excess moisture, which can lead to spoilage. By placing the bananas inside the Nkho and covering them with these specific leaves, the farmer creates a controlled environment that allows the bananas to ripen evenly and attain a desirable yellow colour without the risk of them becoming overly soft or spoiled. The process typically takes around five days, after which the bananas are ripe and visually appealing, making them ideal for consumption or sale.

4.3. Local chamber

In the Mpumalanga Province, one such traditional method involves using a Dulu structure for ripening bananas. Dulu is a small local storage room usually built by women with mud, wood, stones, and grass, where bananas are stored to ripen. Its relative lack of air space, windows, and small size make the room dark with warm

temperatures, regardless of the atmospheric conditions outside. This banana ripening process not only reflects the community's resourcefulness in harnessing Indigenous knowledge systems and deep understanding of local environmental conditions but also highlights the important role of women in sustaining these traditions:

"What we do is go to the field and cut wood and bring it home, and we make a circle using stones, covering the whole place with wood in a circular form. Moreover, women would use mud to cover the places where air can penetrate from inside to outside, and the structure is also roofed with long grass. When the banana is ready for harvesting, we put it inside the Dulu structure for it to ripen. After 5 to 7 days, the banana will be ready for consumption." "We ripen the banana using Dulu, which is a structure made of wood, stones, and grass, with grass roofing. Women were ordered to use mud to patch the spaces where air could penetrate inside the Dulu. Then, the banana is placed there to ripen, and after 7 days, the banana is ready to be consumed." This Dulu technique prevents premature spoilage and ensures banana fruits develop a desirable texture and flavour."

The Dulu storage is an ingeniously constructed ripening chamber that relies on locally sourced materials, such as mud, grass, stones, and wood, to create a controlled environment suitable for the ripening of banana fruits. The chamber is built in a circular form, with wood forming the primary enclosure. Subsequently, stones are placed around the base of the chamber to support the wooden walls and ensure stability. Once the basic framework is structured, the pivotal step of sealing the structure is carried out. Women play a critical role in the process, as they apply mud to patch any gaps or spaces where air might penetrate the chamber, which is essential for maintaining the necessary humidity and warm temperature levels inside to hasten the ripening process. The grass roof provides additional insulation, which ensures that the atmosphere inside the Dulu chamber remains consistent.

4.4. Animal Faeces

Due to its cost-effectiveness and availability, the chicken manure and/or cow dung banana ripening technique is also employed in Mpumalanga. This expression below, an extract of one of the stakeholders who participated in the study, highlights how these natural materials, along with other household items, are utilised to create a controlled environment for ripening banana fruits, showcasing a unique blend of practicality and the Indigenous knowledge system in South Africa.

"I use chicken manure or cow dung to ripen my bananas. I put them in a sack, then add the manure inside along with some newspaper to provide warmth. After that, I cover the bananas with blankets, place them back in the sack, and leave them to ripen. After about a week, an aroma signals that the bananas are ready to be eaten."

This process reflects a practical and sustainable approach to ripening bananas, using organic materials that are readily available and easily accessible to small-scale farmers. In these rural areas, many households have rare cattle, sheep, goats and chickens for domestic consumption and commercial purposes. This animal dungs serve as a natural source of heat, generating the warmth required to accelerate the banana fruit ripening process. When kept in a semi-enclosed space like a sack bag, pot or drum, these materials release heat slowly, thereby creating an ideal microenvironment within the space, further insulated by layers of newspaper and blankets. In this context, a semi-enclosed space is needed to generate and trap the necessary heat for ripening while simultaneously allowing the fruits to breathe, preventing excessive moisture buildup that could potentially lead to spoilage even before it ripens to the desired stage. These elements, combined, help maintain a consistent temperature around the banana fruits, allowing them to ripen evenly in a week. While it appears simple, this technique is an effective approach to ripening banana fruits naturally without the need for modern technology, and it exemplifies how grassroots farmers in rural communities of South Africa maximise the available resources in their entrepreneurial endeavours.

4.5. Maize byproduct

Mufumbu, a byproduct derived from the processing of maize, is one such time-honoured Indigenous banana ripening technique in rural communities. The process of obtaining Mufunbu involves grinding dried maize using

traditional tools—Mutuli and Musi—into a fine powder form. The coarse residue left after shifting to separate the fine maize powder is known as Mufumbu. This maize byproduct, Mufumbu retains a significant amount of heat, making it ideal for efficiently and naturally ripening banana fruits. One of the knowledge holders explains that:

"To ripen the banana fruits, I cut a bunch from the tree, then place it in a sack. I then pour the Mufumbu substance into the sack, ensuring that it surrounds the banana fruits. Once the Mufumbu is in place, I tie the sack securely and cover it with a blanket to help retain the heat. In just a week, the heat from the Mufumbu gradually enhances the banana fruits to ripen. The process is efficient, and after seven days, the bananas are ready for consumption."

Mufumbu's unique heat properties make it an ideal medium for ripening banana fruits. Positioning the banana fruits in a sack and surrounding them with Mufumbu, the local farmers create a warm, insulated atmosphere that accelerates ripening. The use of a blanket further traps heat inside the sack. The ripening technique is effective and resource-efficient, as it utilises a maize byproduct that might otherwise go unused.

4.6. Fruit techniques

Using Indigenous plants and locally available materials like granadilla fruits or ripe banana peels as traditional practices for ripening fruits has long been an essential part of agricultural life in many rural communities, reflecting deep connections to the natural environment and the resources it provides. This technique entails placing ripened banana peels and/or granadilla fruits on the newly harvested bananas and sealing them in the same sack.

"Once the bananas are inside the box, I put some granadilla fruits and ripe banana peels, then cover the box. The fruits and peels are known for generating heat, creating the ideal environment for ripening the bananas. After about a week, the bananas turn a vibrant yellow, signalling that they are ripe and ready for the market. The beauty of this technique is that it ensures all the bananas ripen naturally and uniformly—no sides are left green. This technique is quite similar to another traditional technique using the leaves of an Indigenous tree, which is also known for its effectiveness in ripening bananas."

The effectiveness of this method can also be attributed to the unique properties of the granadilla fruits, which have been recognised for generations for their role in other fruit ripening. Similar results can be achieved using ripe banana peels, a byproduct with comparable heat-producing characteristics. These natural methods ensure that the bananas are ready for consumption or sale promptly and preserve the fruit's quality and colour, making them more attractive to buyers.

5. Discussion of Findings

In Africa, banana fruit ripening techniques, specifically in South African rural areas, are deeply rooted in Indigenous knowledge systems and traditional practices, particularly among small-scale farmers who rely on accessible resources and cost-effective methods (Bantayehu & Alemayehu, 2020). Common practices in this context involve using organic resources such as ashes, chicken manure, cow dung, or maize byproducts to accelerate the banana fruit ripening process. Frequently, these materials are placed in a confined space, such as local pots, sacks, and traditional chambers made of clay, wood, stones and grass alongside the bananas to create warmth and mimic the ethylene gas production that facilitates even ripening. Another notable technique uses the leaves of Indigenous trees such as *Mugwiti* or *Musudzungwane* to cover banana fruits placed in containers, sacks, or any other confined space. The leaves generate heat, temperature, and moisture in the confined space, aiding in the fruits' uniform ripening while enhancing the bananas' flavour and texture. The materials involved in these techniques are not only affordable at the disposal of the local farmers but also eco-friendly and void of health implications, as they minimise chemical use and repurpose natural resources.

Some of these techniques align with traditional banana fruit ripening practices that exist in other regions of the world. For example, in Asia, local farmers commonly and frequently utilise ethylene-releasing organic materials like rice straw or sawdust to ripen bananas (Maduwanthi & Marapana, 2019). A similar pattern was observed in parts of Sri Lanka, where banana farmers use earth pits or clay pots to trap heat and ethylene gas (Chandar & Smith, 2019; Ranaweera, Ampemohotti & Arachchige, 2020). This creates optimal conditions for ripening the fruits evenly. These practices, like those in South Africa, demonstrate a reliance on locally available materials and emphasise the ingenuity of smallholder farmers in adapting to their environments. The use of plant materials, such as banana leaves by local farmers in Latin America and *Musudzungwane* leaves in South Africa, highlights the universal reliance on natural resources to achieve desired banana fruit ripening outcomes.

Despite regional variations, the underlying principle of these traditional banana ripening techniques globally is the creation of a controlled atmosphere to facilitate even fruit ripening, frequently through the manipulation of heat and ethylene gas levels in a confined environment. However, South Africa's Indigenous banana ripening practices differ in their emphasis on specific local resources such as ashes, tree leaves, animal faeces, and maize byproducts, reflecting the region's unique cultural heritage and environmental contexts. Profiling and preserving these traditional techniques are crucial, as they offer sustainable alternatives to the usual contemporary commercial use of artificial banana fruit ripening agents like ethylene gas chambers, that is relatively expensive, as well as calcium carbide, which is banned in many countries resulting in from health-associated risks of the method (Food and Agriculture Organization [FAO], 2020). Drawing parallels between South Africa's Indigenous ripening techniques and those of other regions, it becomes evident that traditional banana fruit ripening practices are valuable for their cultural importance and promise global knowledge-sharing for sustainable agricultural innovations.

Conclusions

Banana ripening techniques in South Africa showcase the richness of the Indigenous knowledge system and the resourcefulness of small-scale farmers who rely on accessible, cost-effective, and eco-friendly methods to achieve optimal ripening outcomes. Using natural materials such as ashes, cow dung, chicken manure, local chambers, maize byproducts, and Indigenous leaves like *Musudzungwane* or *Mugwiti* reflects an environmentally conscious approach rooted in African cultural traditions. Although slightly different, these practices align with global methods observed in Asia, where farmers in India and Sri Lanka similarly utilise locally available resources, such as rice straw, wheat grain, banana leaves, and earth pits, to create controlled ripening environments. Such similarities emphasised the universal reliance on natural processes while highlighting the uniqueness of South Africa's adaptation to its specific cultural heritage and ecological contexts.

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Beata KILONZO is an academic doctor and senior lecturer at the University of Venda. Research interests: Entrepreneurship and rural development

ORCID ID: <https://orcid.org/0000-0001-5336-1270>

John B. Ochanda OGOLA is a Professor at the University of Venda. Research interests: Agronomy and Crop Science

ORCID ID: <https://orcid.org/0000-0002-0036-6091>

Ishmael IWARA is an academic doctor and researcher at the University of Venda. Research interests: Entrepreneurship and rural economic development

ORCID ID: <https://orcid.org/0000-0001-8886-576X>

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REVEALING RESILIENCE: AI ANOMALY DETECTION DRIVEN DESIGN CONSIDERATIONS FOR CYBER PHYSICAL SYSTEMS SUPPORTING CRITICAL INFRASTRUCTURES IN SMALL ISLAND DEVELOPING STATES

Amir Mohammed ¹, Daniel Goitia ², Sheikh Ahad Ahmad ³, Craig Ramlal ⁴

^{1,2,4}*The University of The West Indies, Department of Electrical and Computer Engineering, St Augustine, Trinidad and Tobago*

³*The University of Western Ontario, 151 Richmond Street, London, Ontario, Canada*

E-mails: ¹amirmohammed45@gmail.com; ²daniel.goitia@uwi.edu; ³sheikh.ahmad154@gmail.com; ⁴craig.ramlal@uwi.edu

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Abstract. Ensuring the resilience of Cyber Physical Systems (CPSs) has emerged as a critical priority, particularly for small island developing states (SIDS) and low-resource regions such as the Caribbean. These systems, which tightly couple sensing, computation, and control, are increasingly vulnerable to operational disruptions such as cyber-attacks and sensor faults. In this context, resilience must go beyond disturbance tolerance to encompass real-time anomaly detection (AD), system adaptation, and recovery, ensuring sustained operational safety, reliability, and continuity. This paper uses a machine learning based AD case study to examine the resilience of a Vehicular Cyber-Physical System (VCPS) configured for platooning. Rather than proposing a novel detection method, the study leverages an established framework to extract deeper insights into the resilience needs of VCPSs operating under constrained conditions. For regions with limited redundancy and prolonged recovery times, such as SIDS, the findings emphasise the importance of integrated detection mechanisms that identify threats and support timely and adaptive system responses. This work positions anomaly detection as a diagnostic lens for resilience, contributing to sustainable, secure, and trustworthy transportation infrastructure aligned with broader development goals for CPSs.

Keywords: resilience; anomaly detection; Cyber Physical Systems; cyber attacks; Small Island Developing States

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1. Introduction

Cyberattacks on critical infrastructure are a frequent and escalating global threat, with both the number and sophistication of attacks rising sharply (Riggs et al., 2023). This escalation is driven by rapid digitisation and geopolitical tensions, with weekly attacks on utilities quadrupling since 2020 (KnowBe4, 2024). In recent times internationally, countries have been subjected to such occurrences such as Russian cyberattacks on Ukrainian infrastructure which has risen by nearly 70% (CSIS, 2025), China has experienced an increase of espionage attacks by approximately 150% (CrowdStrike, 2025), while ransomware complaints from U.S. critical-infrastructure organizations have increased by 9% year over year (Internet Crime Complaint Center, 2025). When compared to Latin America and the Caribbean (LAC), this region is currently considered the world's

fastest-growing region for disclosed cyber incidents, averaging about 25% annually over the past decade. LAC also remains among the least protected, with public administration and finance being the most frequently targeted sectors (Cobos & Diao, 2024). In Q2 of 2024, organisations in Latin America experienced a 53% year-over-year rise in weekly attacks, the largest regional jump that quarter (Check Point Team, 2024). Telemetry data from Fortinet has revealed roughly 11% of recorded global exploitation in the Latin America region (FortiGuard Labs, 2025), with a consistent pattern of government and financial entities being mostly targeted from 2023 to 2024 (Positive Technologies, 2023). The industry sector is also a key target, as about one in five ICS (Industrial Control Systems) computers in Latin America had detected or blocked malicious objects in Q1 2025 (Kaspersky Lab, 2025). Some other notable successful cyber-attacks within industry include Stuxnet, Black Energy, WannaCry, Industroyer and Triton (Malik et al., 2023), which contributed to the crippling of national infrastructure systems. Naturally, this highlights the region's vulnerability and inadequate cybersecurity measures amid rapid digital transformation (Brain & Oyadeyi, 2023).

Contemporary critical infrastructures (CIs) comprise interdependent cyber-physical systems (CPSs) alongside human and organisational processes. In this study, we focus on the CPS layer to examine how attacks and fault events at this level affect CPS operation and to identify what must be considered to protect CPS; by extension, these protections shape critical-infrastructure outcomes. CPSs are the integration of computation, communication networks, and physical processes, where embedded systems monitor and control real-world operations (Khalil et al., 2023). These systems underpin CIs such as smart grids, healthcare, military operations, and telecommunications, making them vital to national and regional development (Puig et al., 2016). For emerging economies within small island developing states (SIDS), CPSs are central to modernisation, public safety, and digital economy growth. Consequently, the rising cyber risk to CI translates directly into risks affecting CPSs integrity and reliability (Humayed et al., 2017).

Given these risks, CPS resilience has become an urgent priority, particularly for regions seeking to protect socio-economic progress achieved through digitalisation. In this context, resilience is the capacity to anticipate, absorb, adapt to, and recover from internal faults and external cyber threats (Ross et al., 2021). Without real-time detection mechanisms, CPS become susceptible to cascading failures, jeopardising safe and reliable operation (Palleti et al., 2021). This imperative is even more critical in resource-constrained contexts such as SIDS in the LAC region, where limited redundancy or delayed recovery capacity means a single disruption can have disproportionate effects (Griffor et al., 2017). Building on this, researchers have developed a range of AD strategies for CPS. Prior work spans a wide range of machine learning based approaches which include (i) supervised learners (Biddle & Fallah, 2021) (ii) deep models (Roh et al., 2022), (iii) unsupervised/one-class methods (Song, Hyun, & Cheong, 2021), (iv) hybrid model-based ML schemes (Hao, Yang, & Yang, 2023) and (v) online, transfer or federated variants (Khraisat et al., 2024). These detectors have been applied to false-data injection (FDI) against estimators and sensor fusion, Denial-of-Service (DoS) or jamming on V2X and in-vehicle networks; replay and spoofing misbehaviour in cooperative manoeuvres; and bias/drift faults at sensors and actuators.

Even with these advances, current literature largely focuses on developing individual detection techniques and benchmarking them in scenario-specific attack settings, with limited analysis of the results for resilience outcomes in practice. This constitutes a critical gap, and so our work focuses on attack or anomaly detection (AD) as one of the core processes in the resilience cycle. Rather than proposing a new detector, this study uses a vehicle platooning scenario, an archetypal CPS, directly tied to transportation critical infrastructure, to apply a representative supervised AD method and distil actionable, evidence-based design considerations for CPS resilience. This empirically grounded approach, drawing guidance from observed AD performance in realistic deployment, is especially relevant for Small Island Developing States (SIDS). Although many of the individual insights appear in prior work, they are seldom consolidated into a single, coherent set of AD-informed design considerations for CPS resilience. Our case study provides synthesis and practical guidance for integrating AD

modules into CPS. Framing AD in this way clarifies the capabilities CPS must possess to maintain performance and recover in real operational settings. Accordingly, the contribution extends beyond validating an AD method: it demonstrates how resilience can be operationalised, particularly in resource-constrained SIDS, where transport infrastructure is vital yet fragile and supports digital sustainability agendas aligned with the UN Sustainable Development Goals (UNDP, 2022).

This article is divided into five (5) Sections. Section 1 gives a brief Introduction. Section 2 describes the Vehicle Platoon System (VPS) model as a representative CPS. Section 3 highlights the Anomaly detection method. Section 4 discussed the results produced. Section 5 describes the Insights generated from the study, and Section 6 highlights the conclusion.

2. Vehicular Cyber Physical System – Vehicle Platoon System

The Vehicular Platoon System (VPS) model and its associated components, including the communication topology, control objectives, and anomaly modelling framework used in this study, have been previously detailed (Mohammed et al., 2025). For completeness and continuity, a summary is provided here. The VPS operates using a Predecessor-Follower (PF) communication topology, wherein each vehicle tracks its immediate predecessor's state, allowing for safe inter-vehicular spacing in constrained environments. The vehicle dynamics follow a longitudinal kinematic formulation, with position, velocity, and acceleration represented in a state-space framework as shown in Equation 1, and system architecture depicted in Figure 1.

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix} u(t) \quad (1)$$

The communication structure and control objectives, such as the constant time headway (CTH) policy (Equation 2, Figure 2), are consistent with conventional platoon control strategies.

$$d_{cth} = L_v + (V_p \times t_{cth}) \quad (2)$$

Where d_{cth} is the safety distance the following vehicle must maintain, L_v is the vehicle's length, V_p is the velocity of the predecessor and t_{cth} is the time head way constant. Figure 2 highlights the position and velocity profiles for a 3 VPS, when the safety distance is being maintained.

In VPS-based mobility systems, ensuring safety and operational efficiency is crucial, particularly in regions where traffic accidents have economic and health consequences. This control strategy ensures that each vehicle maintains an adaptive distance based on its velocity and time headway constant, promoting safe driving behaviour and minimising the risk of rear-end collisions, an essential consideration for public transport or logistics networks in resource-constrained regional settings.

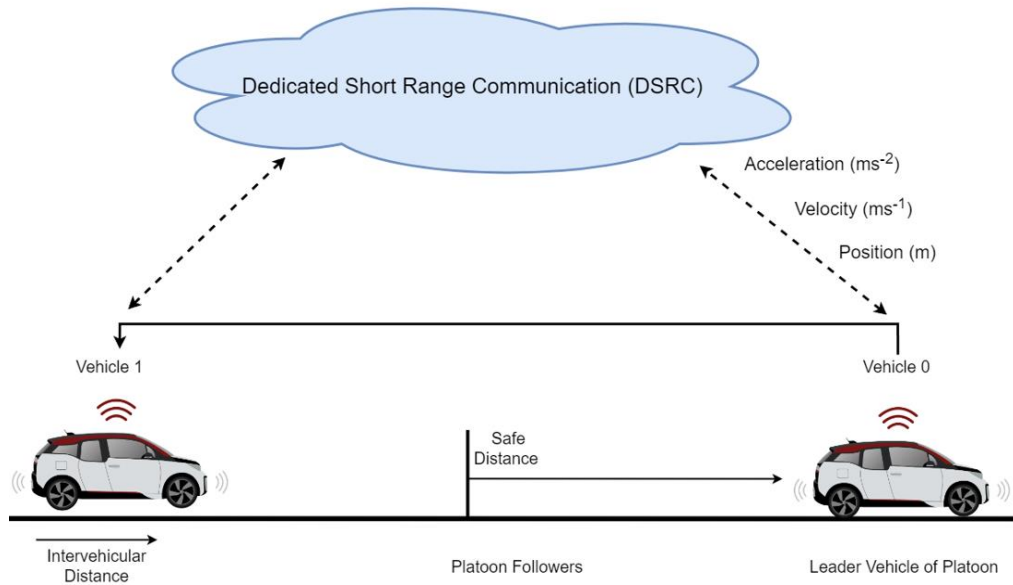


Figure 1. The Vehicle Platoon System
Source: Adapted by the authors from Mohammed et al. (2024)

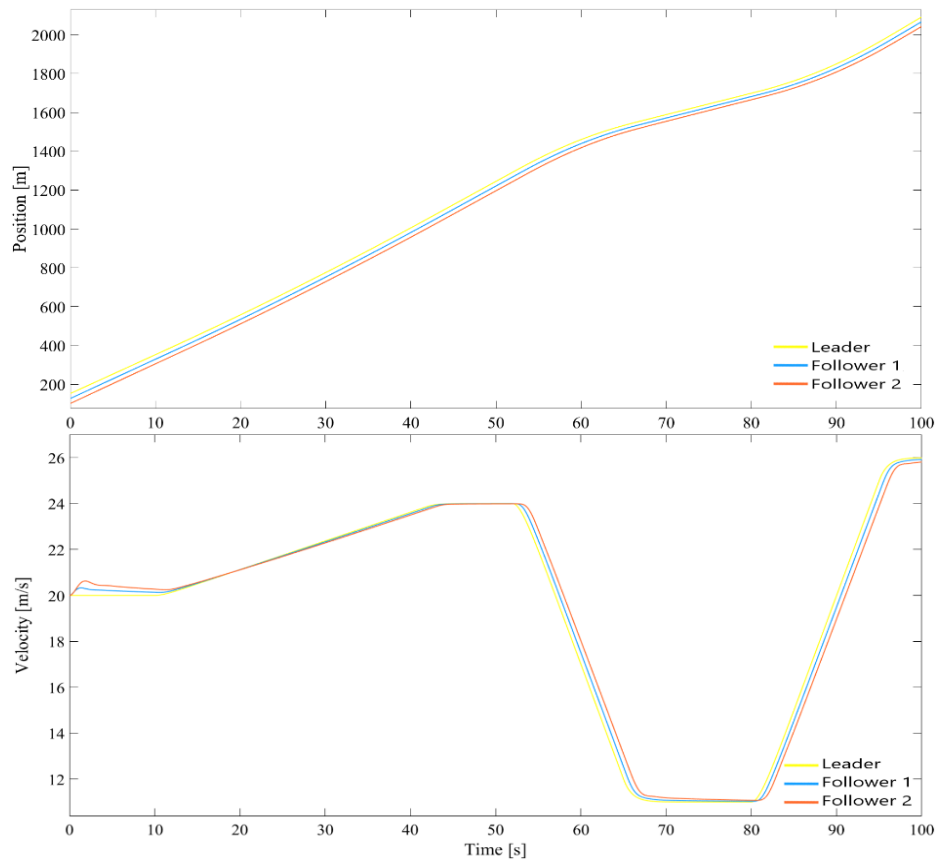


Figure 2. The Position and Velocity Profile for the Platoon System Maintaining the Specified Safety Distance

2.1 Anomaly Modelling

The anomaly scenarios explored in this study also align with our previously published setup. We simulate cyber-physical threats using an FDI attack model to corrupt communicated states such as position and velocity, and a bias fault model to represent sensor degradation in onboard Lidar and Radar systems. These models reflect the dual vulnerabilities faced by CPSs in emerging mobility systems. While full derivations and modelling rationales are provided in (Mohammed et al., 2025) the summary here enables the reader to interpret downstream results in Section 4. The VPS structure and interaction with both cyber and sensor anomalies are illustrated in Figure 3, which provides the foundation for subsequent resilience analysis using machine learning-based AD.

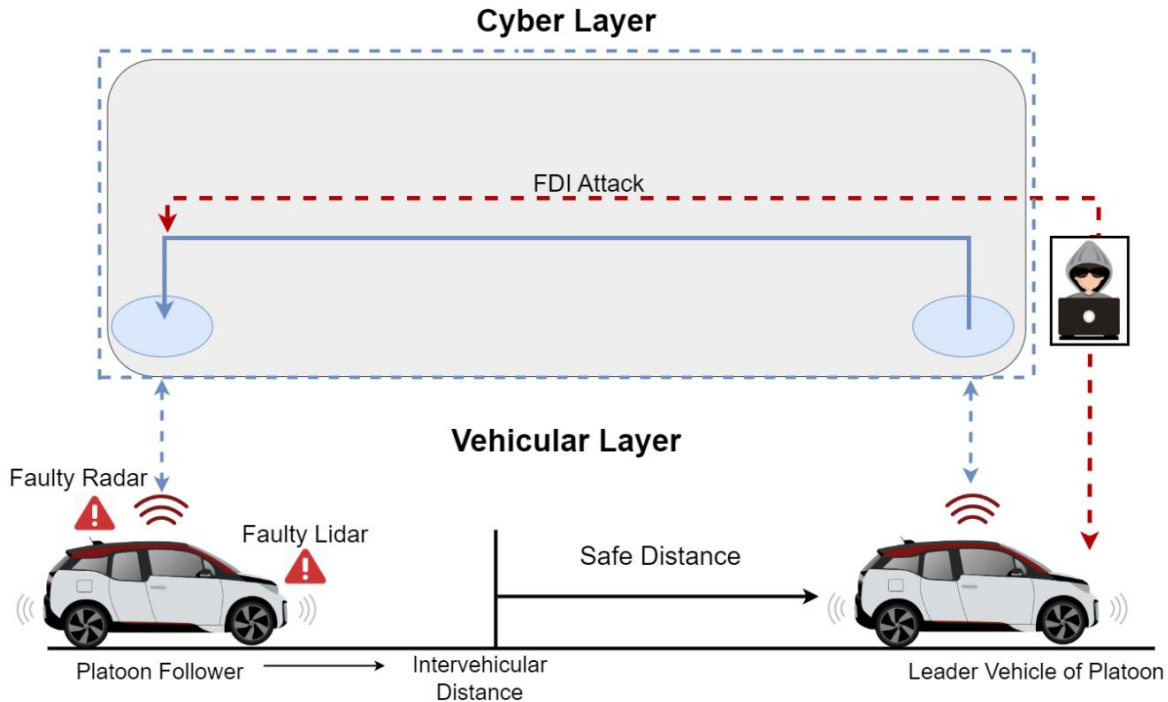


Figure 3. The Position and Velocity Profile for the Platoon System Maintaining the Specified Safety Distance
Source: Adapted by the authors from Mohammed et al. (2024)

2.2 VPS Interaction with Anomaly Model

This section extends the dual-layer anomaly modelling framework originally presented in (Mohammed et al., 2025), where the VPS was analysed under both cyber and fault disturbances. The system architecture, shown in Figure 3, is composed of the Cyber Layer, representing the communication and data-handling infrastructure between the leader and following vehicles, and (2) the Vehicular Layer, encompassing the physical sensors and actuation systems. Together, these layers simulate how the following vehicle maintains a safe inter vehicular distance based on received motion data position and velocity from its leader. The cyber layer is modelled to allow for FDI attacks, wherein adversaries manipulate transmitted state information, such as spoofing or corrupting velocity or position data. Simultaneously, the vehicular layer incorporates intermittent sensor bias faults, simulating real-world issues such as hardware degradation or calibration drift, particularly in onboard Lidar and Radar sensors. These faults and attacks can occur independently or concurrently, introducing complex challenges for system stability and safety. By retaining the anomaly model structure from the prior study while recontextualising it within a resilience-focused evaluation, this section forms the basis for assessing system behaviour under compounding threats. This modelling approach supports realistic resilience testing scenarios aligned with transport infrastructure challenges in resource-constrained regions. Figure 3 reflects this interaction, providing a foundation for the anomaly detection evaluations discussed in later sections.

Cyber Attack and Fault Interaction with VPS model

The VPS is subjected to cyber-attacks and sensor faults. FDI cyber-attacks alter the transmitted state information, such as position and velocity, either individually or simultaneously, at any time and for any duration. Concurrently, the onboard sensors of the following vehicles, namely Lidar and Radar are used to detect the predecessor's distance and velocity, respectively, may be affected by bias faults. These faults can also occur independently or simultaneously, and their magnitude, frequency, and duration are heterogeneous. Moreover, these cyber-attacks and sensor faults can simultaneously occur, making it particularly challenging to maintain reliable state estimation and control. Figure 4 demonstrates the effects of FDI attacks on the transmitted position and velocity data, while Figure 5 illustrates the influence of bias faults on Lidar and Radar sensor measurements. Together, these scenarios underscore the need for a robust and accurate anomaly detection module within the VPS framework.

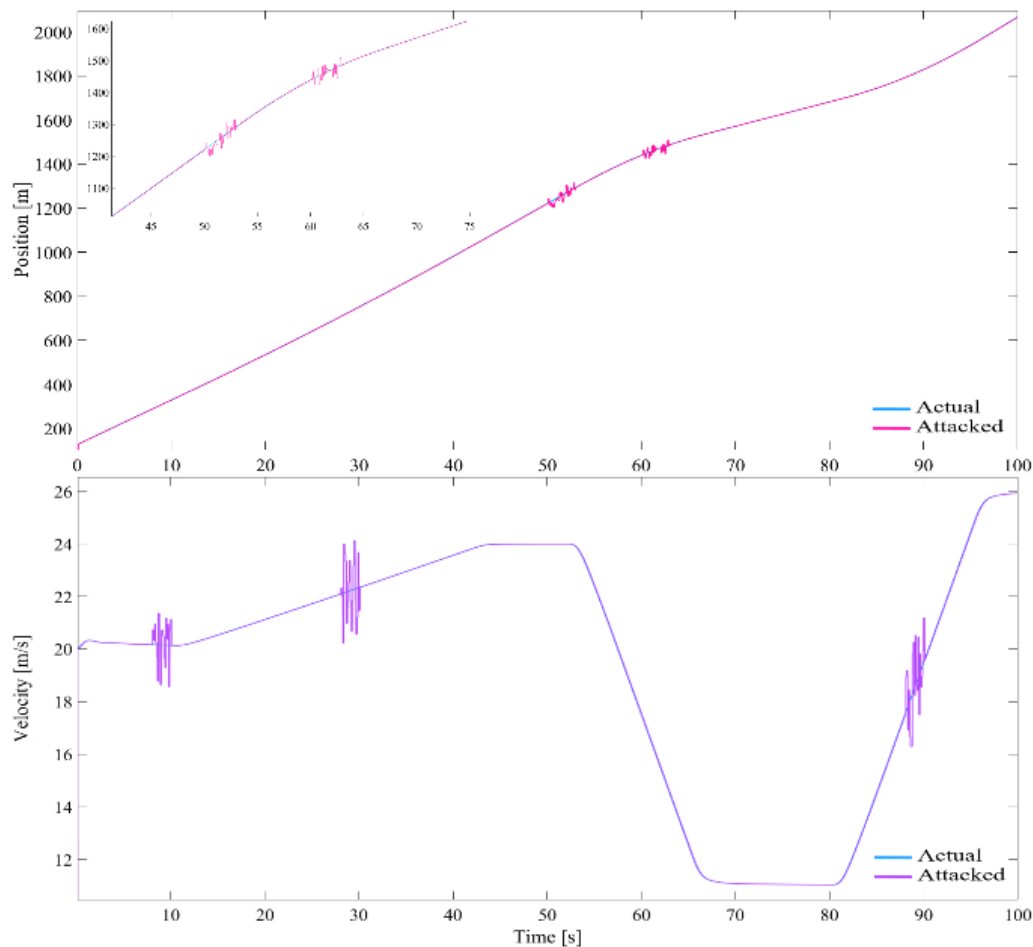


Figure 4. FDI Attacks on Position and Velocity

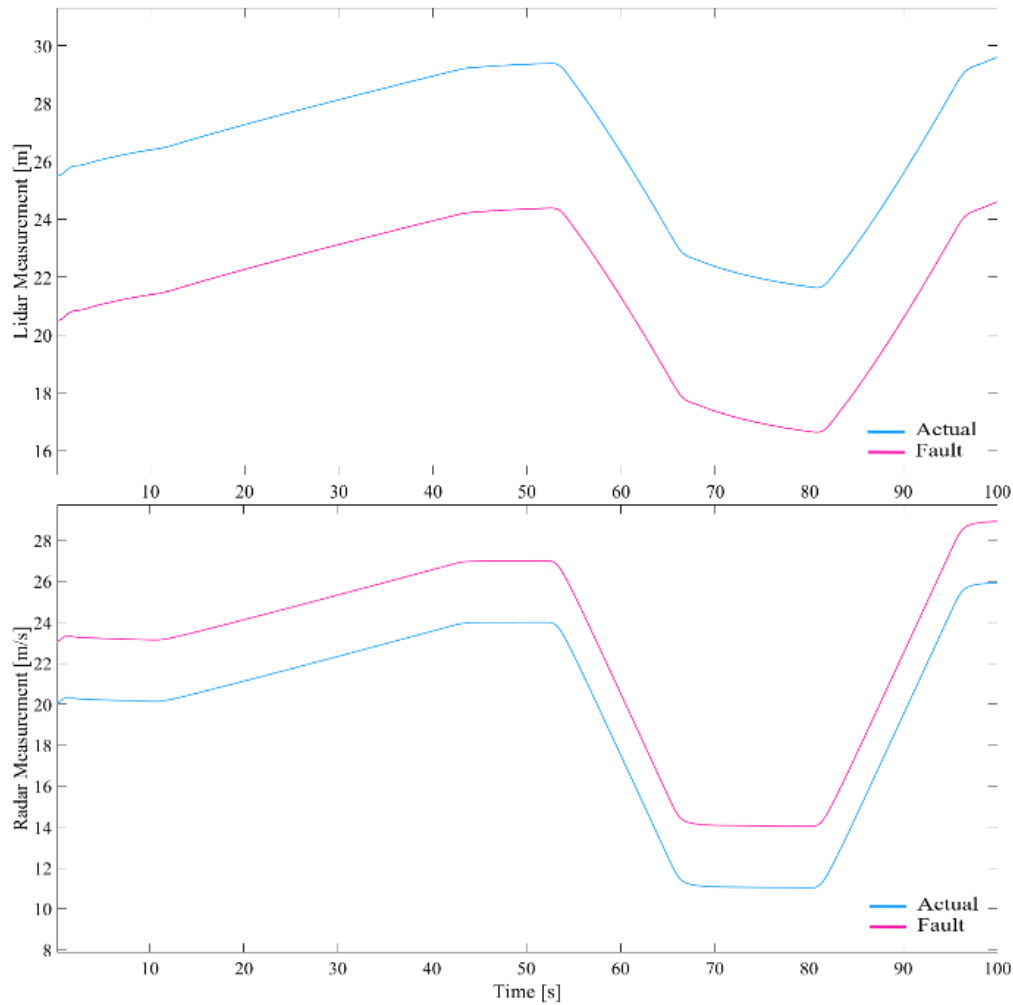


Figure 5. Bias Fault Affecting Both Lidar and Radar

3. Anomaly Detection Method

This section establishes how existing detection mechanisms perform under cyber and sensor anomalies in a VCPS. These empirical observations are later used to extract resilience-related insights such as latency, classification errors, and detection behaviour under concurrent anomalies discussed in Section 4. Thus, this section serves as a diagnostic platform for understanding resilience, not as a contribution to detection algorithm development.

Machine Learning Detection

The detection of FDI cyber-attacks and bias in the sensor measurements for Lidar and Radar is facilitated using supervised learning. This machine learning method uses a known dataset to train an algorithm with a known set of input data features or known responses to make predictions. Utilising supervised learning, four (4) anomaly detectors were trained for the following conditions:

- FDI attacks on position
- FDI attacks on velocity
- Bias faults on Lidar
- Bias Faults on Radar

The training data is formed from 14 independent data sets generated from the simulation. The data sets are as follows: communicated position, communicated velocity, lidar measurements, radar measurements, the change in position, the change in velocity, the change in lidar measurements, the change in radar measurements, position attack class, velocity attack class, position offset, velocity offset, lidar offset, and radar offset. Using different combinations of these data sets, the 4 detectors were trained based on the feature which needed to be predicted such as position, velocity, lidar or radar or a combination of all classes.

Position Anomaly Detector

The position detector was employed to classify the position state, and the classification included two categories: 1) position attacked and 2) position not attacked. In the supervised learning process, the position detector was trained with a diverse mixture of training data. This training set incorporated non-attack data for both position and velocity, as well as FDI attack data on position and FDI attack data on velocity. This comprehensive training approach enabled the detector to gain a deeper understanding of data variations. Using this diverse dataset, the position detector accurately classified the state of the position variable. The position anomaly detector underwent training using the Fine Tree Algorithm within the Classification Learner application in MATLAB 2023a. Details regarding the accuracy of the detector will be discussed later.

Velocity Anomaly Detector

The velocity detector determined whether the velocity state was under attack or not, employing a classification approach like that of the position anomaly detector. The velocity detector underwent training with a diverse set of training data in the supervised learning process. In this instance, the velocity detector included non-attack data for both position and velocity, as well as FDI attacks on position and FDI attacks on velocity data in its training set. This inclusive training approach enabled the velocity detector to classify the state of the velocity variable accurately. The Medium Tree Algorithm was employed to train the velocity detector.

Lidar Anomaly Detector

The Lidar detector was used to classify the state of the Lidar sensor. The classification consisted of either 1) fault detected or 2) no fault detected. In a similar manner, the Lidar detector was trained using a mixture of varying training data within the supervised learning process. In this case, the Lidar detector incorporated several varying scenarios that were applied to the sensor, allowing the Lidar detector to classify the faults accurately. These scenarios consisted of non-faulty data on both the Lidar and Radar sensors, along with faulty data on Lidar and Radar. The algorithm which was used was Ensemble Learning – Bagged Trees for this anomaly detector.

Radar Anomaly Detector

The Radar detector was used to classify the state of the Radar sensor. The training process was similar to that of the Lidar detector using the variation in data for the trained model. The algorithm which was used to train the Radar anomaly detector was a bi-layered neural network.

4. Results

This section highlights the results for the supervised learning anomaly detection modules. The results are broken into three main categories:

- Anomaly Detection for Position, Velocity and Radar
- Anomaly Detection for Position, Velocity and Lidar
- Anomaly Detection for Position, Velocity, Radar, and Lidar

4.1 Anomaly Detection – Position, Velocity and Radar

In the first scenario the system undergoes FDI cyber-attacks on position and velocity with faults on the Radar sensor. Table 1 gives a detailed breakdown of the cyber-attacks, faults and the associated times of execution during the simulation where A represents the affected variable. In Table 1, position is affected by an FDI cyber-attack, which intermittently modifies the real value of position by random values within the range $A \pm 18\text{m}$. Therefore, during the associated attack times, between the period of 25(s) – 32(s), the true value will be modified. Similarly, this attack is executed within the listed timelines as seen in Table 1 associated with the position variable. Velocity is also affected by FDI attacks with its corresponding attack times, while the Radar sensor is affected by a bias fault during the associated fault time as seen in Table 1. This scenario essentially encompasses the presence of FDI cyber-attacks and bias faults.

Figure 6 highlights the results for each of the anomaly detectors for position, velocity, Radar and Lidar sensors. Therefore, considering Scenario 1, the performance of the anomaly detection for both position and velocity states can be seen in Figure 6. The plot consists of lows (0) and highs (1), where a low represents no attack and a high represents an anomaly is detected. Figure 6 consists of two plots for each variable: 1) A black broken line, which represents the anomaly window, and 2) A grey broken line, which represents the anomaly detection generated by the trained models for each variable. In the case of position and velocity the grey broken line represents attack detection, while in the case of the Lidar and Radar the grey lines represent fault detection.

There are four possible outcomes which can exist in the case of anomaly detection: 1) true positive (TP), which means that the detection correctly identified an anomaly, 2) true negative (TN), where the detector correctly identified the absence of an anomaly, 3) false positive (FP), where the system detected an anomaly when there wasn't any existing and 4) false negative (FN) which means that the anomaly detectors detected no anomaly when there was indeed an anomaly. As shown in Figure 6, there are a few recorded instances of FNs and FPs for the anomaly detection associated with the position variable. The anomaly detector for velocity recorded very few FPs. In the case of Radar one instance of a FP was recorded. For each of the associated anomaly detection rates, the performance is very accurate overall, with a few misdetections taking place during the run time of the simulation. The details surrounding the performance of the anomaly detection will be discussed later.

Table 1. The Magnitude of the FDI Cyber Attacks and Bias Faults When Position, Velocity and Radar are Affected

Affected Variable	Cyber Attack/ Fault	Attack Rate %	Attack Time (s)
Position (m)	(FDI) $A \pm 18$	100	25[s] – 32[s] 55[s] – 70 [s] 111[s] – 123[s] 125[s] – 140[s] 130[s] – 135[s]
Velocity (ms^{-1})	$A \pm 10$	100	32[s] – 39[s] 70[s] – 90[s] 100[s] – 109[s] 118[s] – 135[s] 140[s] – 150[s]
Radar Sensor (ms^{-1})	-5 +6 -6 +5 +4	100	10[s] – 15[s] 30[s] – 45[s] 50[s] – 67[s] 79[s] – 95[s] 121[s] – 130[s]

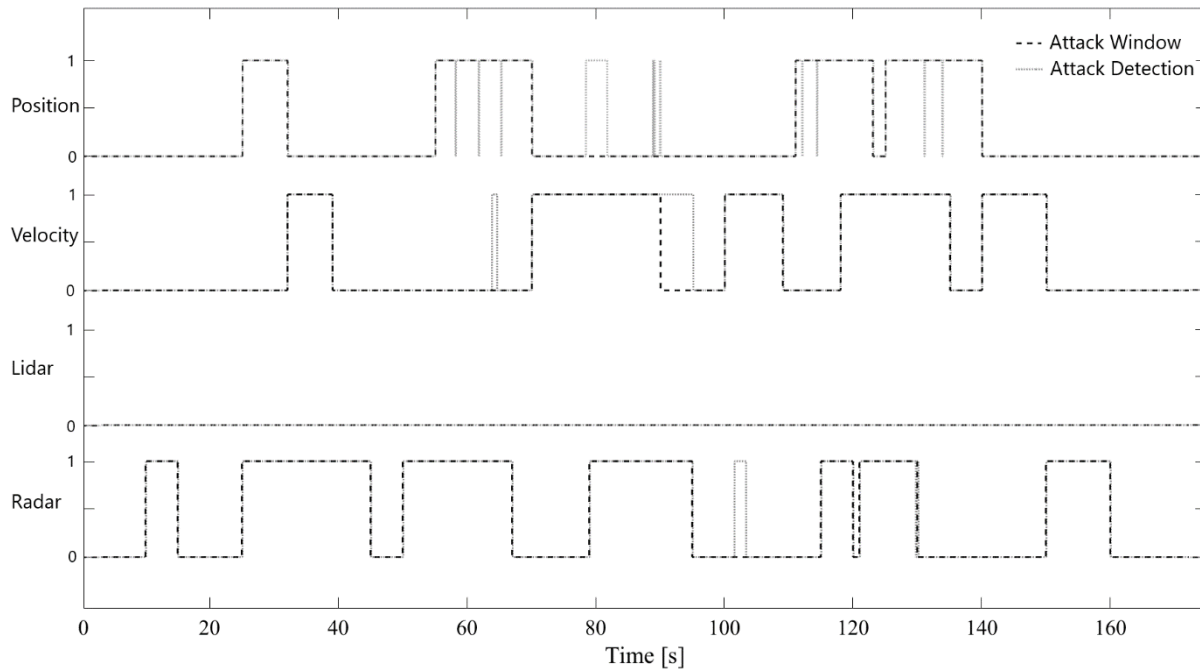


Figure 6. The Associated Anomaly Detection Produced by the Supervised Trained Model for Scenario 1

4.2 Anomaly Detection – Position, Velocity and Lidar

Table 2 highlights the associated execution times of cyber-attacks and faults which affect the position, velocity and Lidar sensor. Figure 7 presents the detection rate for each of the affected states and Lidar sensor. In the case of the anomaly detection rate for the position affected by FDI, it can be seen from Figure 7 that there were a few instances of FPs and FNs. In a similar situation the trained anomaly detector for velocity experienced just one instance of a FN and two instances of a FP. The attack window, as compared to the detection rate, is almost ideal, highlighting the detector's overall good performance. Lastly, there were no FPs or FNs from the detector for the attacked Lidar's sensor during this scenario.

Table 2. The Magnitude of the FDI Cyber Attacks and Bias Faults When Position, Velocity and Lidar are Affected

Affected Variable	Cyber Attack/ Fault	Attack Rate %	Attack Time (s)
Position (m)	(FDI) $A \pm 18$	100	25[s] – 32[s] 55[s] – 70 [s] 111[s] – 123[s] 125[s] – 140[s] 130[s] – 135[s]
Velocity (ms^{-1})	$A \pm 10$	100	32[s] – 39[s] 70[s] – 90[s] 100[s] – 109[s] 118[s] – 135[s] 140[s] – 150[s]
Lidar Sensor (ms^{-1})	8 -12 11 -9 6	100	10[s] – 15[s] 20[s] – 30[s] 30[s] – 45[s] 60[s] – 80[s] 90[s] – 110[s]

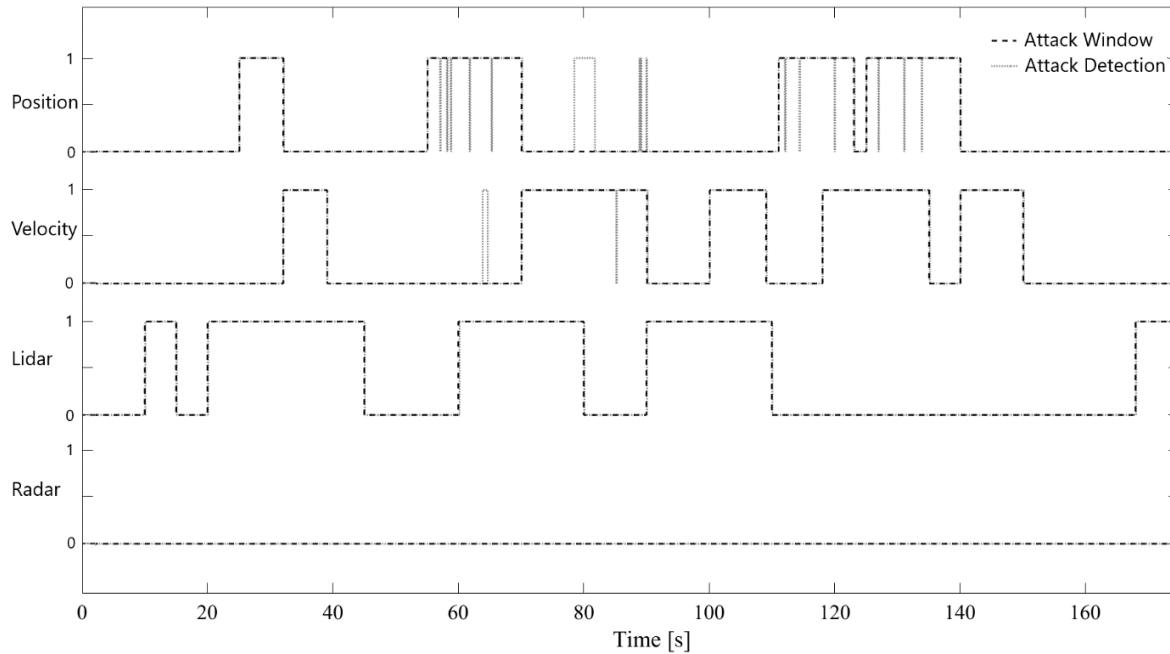


Figure 7. The Associated Anomaly Detection Produced by the Supervised Trained Model for Scenario 2

4.3 Anomaly Detection – Position, Velocity, Lidar and Radar

Table 3 highlights the execution times of cyber-attacks affecting the position and velocity states, along with bias faults on the Lidar and Radar sensors. Figure 8 shows the detection rate for each affected state and sensor. In the case of the detection rate for the position variable affected by FDI attacks, a limited number of FNs were generated with no FPs.

Table 3. The Magnitude of the FDI Cyber Attacks and Bias Faults When Position, Velocity, Lidar and Radar are Affected

Affected Variable	Cyber Attack/ Fault	Attack Rate %	Attack Time (s)
Position (m)	(FDI) $A \pm 18$	100	25[s] – 32[s] 55[s] – 70 [s] 111[s] – 123[s] 125[s] – 140[s] 130[s] – 135[s]
Velocity (ms^{-1})	$A \pm 10$	100	32[s] – 39[s] 70[s] – 90[s] 100[s] – 109[s] 118[s] – 135[s] 140[s] – 150[s]
Lidar Sensor (ms^{-1})	8 -12 11 -9 6	100	10[s] – 15[s] 20[s] – 30[s] 30[s] – 45[s] 60[s] – 80[s] 90[s] – 110[s]
Radar Sensor (ms^{-1})	-5 6 -6 5 4	100	10[s] – 15[s] 30[s] – 45[s] 50[s] – 67[s] 79[s] – 95[s] 121[s] – 130[s]

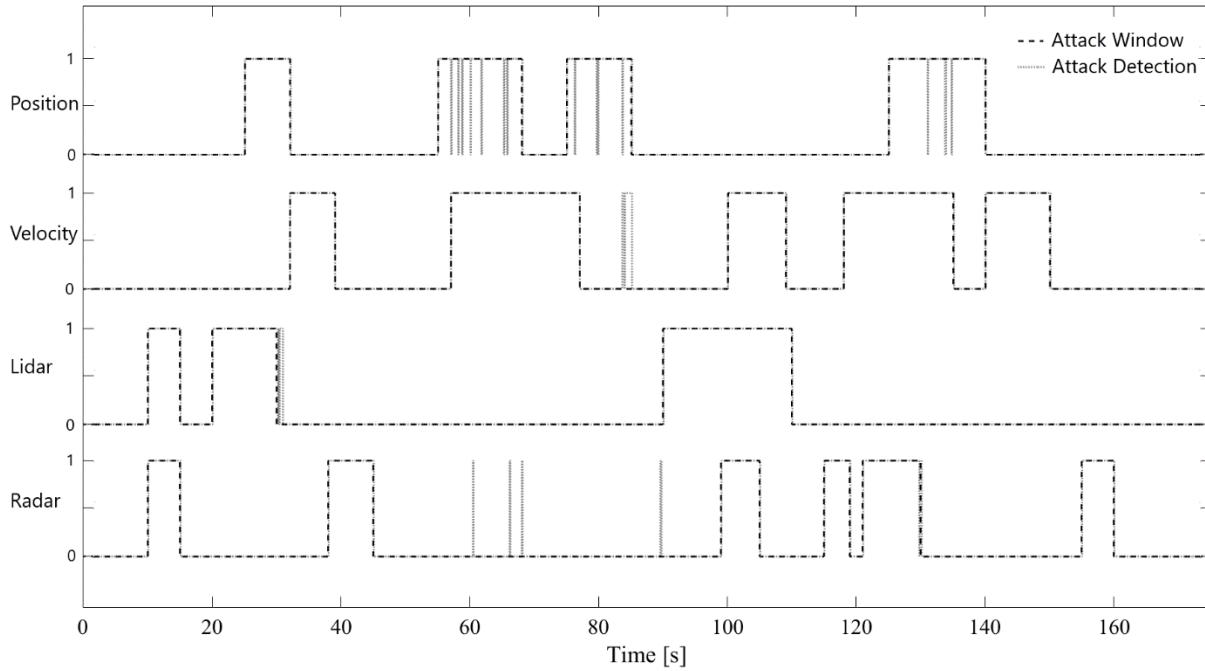


Figure 8. The Associated Anomaly Detection Produced by The Supervised Trained Model for Scenario 3

The anomaly velocity detector recorded a limited number of FPs with no record of any FNs. In the case of Lidar, the detection rate recorded one instance of a FP, a limited number of FPs for Radar and no FNs for both sensors. This scenario showed and overall, very good performance of all detectors.

4.4 Performance of Anomaly Detection Scheme

The popular performance metric used to evaluate the accuracy of trained machine learning models is known as the F1 score. The F1 score can be calculated using recall and precision metrics. The recall is defined as the portion of instances that are correctly predicted as positive to the actual size of the attack class and can be calculated using Equation 5, while the Precision is computed using Equation 6 (Haq, Khan, & Akhunzada, 2021; Khan, Sivaraman, & Honnavalli, 2020).

$$Recall = \frac{TP}{TP + FN} \quad (5)$$

$$Precision = \frac{TP}{TP + FP} \quad (6)$$

Therefore, using the Recall and Precision values the F1 score can be calculated using Equation 7. Naturally a F1 score ranges from 0 – 1 with 0 being worst case and 1 being best case.

$$F1 = \frac{2 * Precision * Recall}{Precision + Recall} \quad (7)$$

Tables 4, 5 and 6 represent the F1 scores for the anomaly detection method for the three main situations simulated. The anomaly detection scheme produced accurate results based on the high F1 scores computed for each scenario. Additionally, the F1 scores recorded were comparable to other existing anomaly detection methods

presented in literature (Fails & Olsen, 2003; Abu Al-Haija & Zein-Sabatto, 2020; Alkahtani & Aldhyani, 2021; Almasoud et al., 2022; Alsaade & Al-Adhaileh, 2023; Alsulami et al., 2022; Biddle & Fallah, 2021; Hamza et al., 2022; Oucheikh et al., 2020; Roh et al., 2022; Sarwar et al., 2022; Song, Hyun, & Cheong, 2021).

Table 4. The F1 score for the Position, Velocity and Radar Anomaly Detection Scenario

Position, Velocity and Radar						
Detector	TP	FP	FN	Precision	Recall	F1 - Score
Position	483	39	7	0.9253	0.9857	0.9545
Velocity	630	62	0	0.9104	1	0.9531
Radar	819	19	1	0.9773	0.9988	0.9879

Table 5. The F1 score for the Position, Velocity and Lidar anomaly detection scenario

Position, Velocity and Lidar						
Detector	TP	FP	FN	Precision	Recall	F1 - Score
Position	479	39	11	0.9247	0.9776	0.9545
Velocity	629	12	1	0.9813	0.9984	0.9898
Lidar	759	0	1	1	0.9987	0.9993

Table 6. The F1 score for the Position, Velocity, Lidar and Radar anomaly detection scenario

Position, Velocity, Lidar and Radar						
Detector	TP	FP	FN	Precision	Recall	F1 - Score
Position	435	3	15	0.9932	0.9667	0.9797
Velocity	630	17	0	0.9737	1	0.9867
Lidar	350	7	0	0.9804	1	0.9901
Radar	359	6	1	0.9836	0.9972	0.9903

5. Insights from Case Study

As our results have shown, scenarios with F1-scores exceeding 95% still experienced misdetections. This reinforces a crucial systems level insight, resilience must extend beyond detection to include response, recovery, and learning mechanisms. In the context of VPSs, where system coupling and real-time operation amplify the risks of delay or mis-reaction, resilience must be framed as a dynamic, integrated property rather than a binary detection outcome. To this end, the authors present a set of critical insights derived from both simulation results and systems thinking that offer a more nuanced understanding of CPS resilience. While these insights may individually surface across various publications, they are rarely compiled and articulated collectively in a single case study.

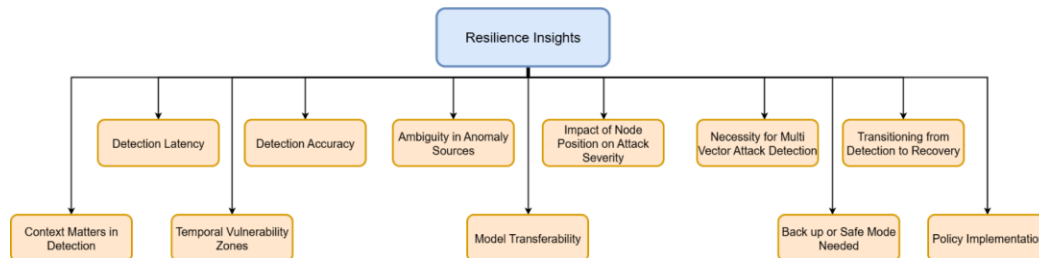


Figure 9. The Insights Drawn from the Case Study

Figure 9 above illustrates key dimensions of resilience insights that will be used to provide a structured and actionable understanding of how anomaly detection performance translates into broader system resilience challenges and opportunities.

5.1 Detection Latency

In the simulated scenarios presented in Figures 6 – 8, the trained anomaly detectors experienced minimal detection delay with faults and cyber attacks detected almost immediately within their onset windows. This outcome reflects the accuracy of the trained detector model and, by extension, the nature of the attacks implemented. In this case study the attack surfaces are relatively limited, and the classifiers were trained under controlled conditions. As such, the issue of detection latency did not manifest in the evaluated test cases. However, this absence of delay under idealised conditions should be given closer attention. In more complex, real-world settings, particularly those involving multiple attack surfaces, evolving anomaly types or higher-dimensional feature spaces, latency in anomaly identification becomes a critical vulnerability. Aspects such as increased model complexity, limited training coverage, or dynamic environmental noise can all introduce subtle delays in detection, even with high offline accuracy. In VPSs, even brief detection delays on the order of 1.5 – 3.9 seconds can cause instability and degrade safety. For instance, a misbehaviour detection system (MDS) with even a modest processing lag may fail to prevent collision risks, especially if fallback modes like Adaptive Cruise Control (ACC) are not sufficiently reactive (Kalogiannis et al., 2022). By contrast, low-latency detection architectures such as those using transformer-based models with decision intervals around 100 ms (Li et al., 2024) demonstrate significant promise in maintaining resilience under high-risk operational conditions. This contrast underscores the importance of developing and deploying detection mechanisms that prioritise not just accuracy, but also timeliness, to ensure the resilience of vehicular platoons under adversarial conditions. This reinforces the point that resilient CPS design must prioritise not only detection accuracy, but also detection timeliness.

5.2 Detection Accuracy (False Positives and False Negatives)

Understanding the impact of FNs and FPs is essential when designing resilient AD systems in VPSs. From the detection plots, there is the existence of FPs and FNs. A FN occurs when an actual anomaly such as FDI or a sensor fault remains undetected. This is arguably the most dangerous situation which can exist, particularly in a tightly coupled system like vehicle platoons. In this situation, misdetection can allow malicious data to enter control loops, resulting in instability. Since the system remains unaware of the ongoing threat, no proper corrective actions can be initiated, leading to an amplified effect downstream which can result in the violation of safety constraints without any warning. As such, many resilience frameworks adopt an approach that prioritises a lower FN rate even at the cost of having slightly elevated FP rates. In safety-critical applications, the cost of missing a real threat naturally outweighs the inconvenience of having a false alarm. In contrast, FPs occur when normal system behaviour is mistakenly flagged as anomalous. While not directly hazardous, FPs can degrade system performance and operational efficiency. False alarms can trigger unnecessary emergency responses like braking, rerouting, or failover control, which increase control effort, fuel use, computational load, and actuator wear, ultimately degrading system performance and operational efficiency. For human-in-the-loop scenarios, frequent false alarms may also lead to operator fatigue, causing delayed or ignored responses to future valid alerts. If unaddressed, high FP rates can eventually result in suppression of alerts altogether, undermining the aspect of trust in the system. Therefore, while FNs may be classed as having greater immediate risks, FPs must be given equal consideration to ensure the reliability, safety, and long-term trustworthiness of the system.

Additionally, FPs and FNs exert broader resilience implications. One key concern is the temporal persistence of misclassifications, whether an FN or FP is quickly corrected or remains unresolved. From a resiliency perspective, these effects underscore the need for temporal awareness in detection systems. Detection models must not only aim to classify accurately in the moment but also include mechanisms for re-evaluating prior classifications over time using updated context. Estimating the confidence of past decisions, especially when operating under uncertainty, is also key. Thus, resilience is not just about getting it right, but about getting it right at the right time and correcting misclassifications before they propagate into significant operational disruption. Therefore, detection systems should be cost-aware, dynamically weighing error penalties in response to context (Schaberreiter et al., 2024).

5.3 Ambiguity in Anomaly Sources (Sensor Faults Mimic Attacks)

The behavioural similarity between sensor faults and cyber-attacks highlighted in Table 1 proves FDI and the bias sensor fault to be a key challenge from the perspective of accurate anomaly attribution. Both types of anomalies can trigger similar deviations in residual signals calculated as the difference between estimated and observed values, making it difficult to distinguish their true origin. While sensor bias faults often introduce persistent deviations due to hardware degradation, FDI attacks intentionally inject malicious perturbations that mimic such patterns to evade detection. This resemblance between faults and attacks is not coincidental; modern adversarial strategies frequently exploit faults like signatures to bypass anomaly detection, especially those based on model prediction or state estimation (Guo, Sun, & Pang, 2023). As a result, the AD strategy may correctly detect an anomaly but misclassify its nature, mistaking sensor drift for an attack, or worse, failing to recognise an attack disguised as a fault. The implications are nontrivial. If a true fault is misclassified as an attack (Roy & Dey, 2023), this may trigger inappropriate countermeasures, wasting resources and inducing service disruptions. Conversely, an attack disguised as a minor fault (Yang, Murguia, & Lv, 2023) could propagate undetected through the control architecture, compromising safety, coordination, and trust, especially in multi-agent scenarios like vehicle platoons, where even one misdiagnosis can have detrimental effects.

Therefore, resilient AD demands fine-grained attribution based on a deep understanding of the behavioural overlaps between faults and attacks. Developing differentiation-aware detection logic able to contextualise anomalies, analyse residual dynamics over time, and incorporate system-level cues is essential to ensuring that appropriate and proportionate responses are taken. In safety-critical domains, mistaking one for the other is not just a classification error; it's a resilience failure. To address this, modern research emphasises the need for multi-layered detection architectures capable of identifying anomalies and attributing them accurately (Rendall et al., 2025).

This consideration becomes even more critical in the context of larger, high-dimensional systems where the number of attack surfaces increases exponentially. As systems grow in complexity, featuring more sensors, actuators, communication links, and interdependent components, the number of potential points of failure or vulnerability expands. In such settings, it is increasingly plausible for multiple anomalies to occur simultaneously, due to coordinated cyber-attacks or cascading sensor faults. The challenge of accurate anomaly attribution is affected by this dimensionality; the residual space becomes more intricate, and the overlap between fault and attack-induced signatures becomes harder to delineate. Therefore, scaling AD strategies to these more complex environments requires improved sensitivity and specificity and robust contextual reasoning capable of interpreting anomaly behaviour across multiple dimensions and agents.

5.4 Impact of Node Position on Attack Severity

In VPSs, the lead vehicle acts as the reference node by transmitting trajectory information to the following vehicles. Consequently, cyber-attacks targeting this transmitted data can directly compromise the first follower, potentially causing cascading disruptions throughout the platoon. As shown in (Kalogiannis et al., 2022), anomalies affecting Follower 1 can propagate through communication and control loops, amplifying spacing and velocity errors in downstream vehicles. This chain of reactions highlights a critical systemic vulnerability; the compromised integrity of a single upstream agent can destabilise the entire formation due to its role in coordination and synchronisation. From a resilience perspective, this highlights the importance of prioritised detection and protection mechanisms at the lead vehicle. Given that the platoon's overall stability can be greatly influenced by Follower 1's behaviour, resilience-enhancing strategies should be taken specifically on this node. Ultimately, ensuring system resilience is not solely a matter of global detection coverage but also of strategically identifying and fortifying high-impact nodes. Beyond this immediate risk, several broader system design implications emerge that can further enhance resilience in cooperative platooning. One critical consideration is the need to avoid rigid, single-point dependencies by enabling dynamic role reassignment such that if the first following vehicle exhibits anomalous behaviour or fails, another agent within the platoon can assume leadership.

Additionally, rather than treating the information as fully trusted, trust-aware coordination can be employed wherein follower vehicles continuously evaluate the reliability of received signals based on behavioural consistency, local sensing, or consensus with peer vehicles (Hermann et al., 2024). This highlights that resilience in vehicular platoons is not solely about detecting anomalies but about building architectural flexibility, distributed intelligence, and adaptive response capabilities into the system, particularly around critical nodes like that of the lead vehicle.

5.5 Necessity of Multi-Vector Attack Detection Multi Attack Detection is Critical

While the detection framework demonstrated commendable performance under isolated threat conditions, the results clearly reveal that the introduction of additional or unforeseen attack types, especially those for which the detector is not adequately trained, can naturally degrade accuracy and lead to system failure. In Tables 4–6, the simultaneous presence of FDI and sensor faults led to variations in the F1 score, indicating that multi-source disturbances introduced some sort of ambiguity within the classification. This points to a broader concern, as the number of attack surfaces and simultaneous anomalies increases, detection models trained on singular or simplified attack conditions may not generalise well. Such limitations, where misclassification of an attack or falsely flagging normal behaviour can have cascading effects. Therefore, multi-class and multi-modal attack detection becomes essential as we scale toward more complex, real-world environments (Bogdoll et al., 2024). These scenarios often involve blended disruptions, adaptive attack strategies, and variable system contexts. From a resilience perspective, this means detection mechanisms must evolve beyond binary classification or unimodal thresholds. Instead, systems must integrate context-aware, compositional detection architectures that can distinguish overlapping threats, assign confidence levels, and adapt to operational modes (Chen, Shin, & Dadrás, 2024). Failing to do so may result in partial situational awareness, delayed containment, and ultimately, reduced resilience under compound stress conditions.

5.6 Transitioning from Detection to Recovery

Accurate and timely detection is critical for CPS resilience, as it is one of the major steps in the resilience cycle. Recovery, the process of returning to nominal behaviour after an anomaly, represents a distinct phase in the cycle. System resilience must therefore include detection and isolation and the speed and effectiveness of re-stabilisation mechanisms. Recovery effectiveness can be quantified using metrics like mean time to recovery (MTTR), which reflects how quickly a system returns to safe and stable operation. In vehicular platooning, prolonged recovery even after accurate anomaly detection can lead to spacing inconsistencies, control jitter, or unnecessary disengagement of automated driving features (Zhu et al., 2023). As such, a truly resilient system must be engineered with recovery in mind. Several additional factors influence this recovery process. One is the availability of fallback mechanisms such as adaptive cruise control, local relative sensing, or degraded control modes that allow the system to maintain safe operation during re-stabilisation. Another is the coordination of recovery across agents, particularly in multi-vehicle systems where unilateral recovery may lead to misaligned behaviour. In this context, graceful degradation becomes a key design goal, rather than full system shutdowns; resilience can be preserved by transitioning to lower-risk operational states.

Lastly, recovery strategies should incorporate learning from past anomalies (Nelson et al., 2025). Logging FPs and FNs along with associated recovery durations and conditions enables future predictive calibration. Systems equipped with self-healing logic are better able to adapt to evolving threats and unforeseen disturbances. Including recovery metrics such as post-anomaly overshoot, damping rate, and control effort in system evaluation frameworks also provides a more complete picture of resilience. Ultimately, embedding recovery as a core design objective enhances robustness and long-term reliability and safety in complex, cyber-physical environments.

5.7 Context Matters in Detection

Operational context significantly influences the effectiveness and consequences of AD. Detection sensitivity varies with factors like vehicle speed, environmental conditions, and traffic density. In platooning where vehicles

travel at high speeds, anomalies such as sensor faults or cyber-attacks may trigger quicker detection due to the generation of prominent system deviations. However, the same anomalies can cause more severe consequences, including amplified spacing errors or instability, making timely and context-aware detection even more critical. For instance, an FDI attack or sensor drift that might be benign or tolerable during lower speeds can result in severe effects at higher speeds, where reaction time is reduced and safety margins are tighter. This reveals that detection thresholds, filtering algorithms, and control logic should have the ability to be adaptive based on real-time operational context, whether the system is accelerating, cruising, or decelerating (Park, 2024). Context-aware detection frameworks, which adjust their sensitivity and response logic based on situational parameters, offer a promising direction to enhance resilience and reduce false alarms without compromising responsiveness under critical conditions.

Building upon this, context-aware systems can further enhance resilience by leveraging historical data to establish behavioural baselines under varying conditions. Through continuous learning, these systems can more accurately distinguish between legitimate operational deviations and anomalies. For instance, temporary spikes in acceleration might be expected during overtaking manoeuvres, whereas similar patterns during steady-state cruising could signal a potential fault or cyber intrusion. Integrating contextual cues from both internal states and external indicators into the detection logic allows for more accurate decision-making. This is crucial in reducing both FPs and FNs, ultimately contributing to safer and more reliable VCPs performance. To extend this further, context-awareness should not be limited to immediate driving behaviour but should also encompass higher-level contextual dimensions such as temporal patterns, spatial location, and mission-critical priorities. Temporal intelligence allows detection systems to align expectations with the system's operational phase. When external signals are incorporated into the detection process, they enrich the model's ability to interpret observed behaviour in its proper context (CAR 2 CAR Communication Consortium, 2021). Ultimately, embedding contextual adaptability into anomaly detection frameworks is fundamental to delivering resilient, trustworthy CPS performance in dynamic and uncertain real-world environments.

5.8 Temporal Vulnerability Zones

The concept of temporal vulnerability zones highlights that not all moments within a system's operational timeline carry equal risk. Figure 4 illustrates FDI attacks during acceleration phases; consequently, this can create a destabilising effect on system operation when compared to time zones with cruising velocities. During acceleration, vehicular systems operate under dynamic transitions, creating a narrower tolerance for external disturbances. In contrast, cruising phases generally involve steadier trajectories and more predictable responses, offering an inherent buffer against anomalies. Recognising these windows of heightened susceptibility allows for more strategic and efficient allocation of detection and mitigation resources. From a resilience standpoint, this supports the development of systems capable of dynamically elevating anomaly detection sensitivity during high-risk transitions such as acceleration, deceleration, or lane merging. Moreover, embedding awareness of temporal vulnerability zones into predictive control models (Bonzanini, Mesbah, & Di Cairano, 2024) and adaptive alert scheduling mechanisms allows the system to anticipate potential disruptions rather than merely react to them. This enhances resilience by minimising disturbance propagation, reducing response latency, and supporting quicker containment and recovery. Ultimately, incorporating temporal intelligence into anomaly detection frameworks transforms resilience from a reactive safeguard into a situationally aware, anticipatory capability optimised to protect the system precisely when it is most exposed to risk.

5.9 Model Transferability

Model transferability is a foundational aspect of resilience in CPSs (Sajjadi, Dinmohammadi, & Shafiee, 2025), especially in vehicular platooning where dynamic environmental changes are frequent. While the trained models demonstrate strong performance under the conditions they were developed and tested on, their effectiveness may significantly decline when exposed to unfamiliar or unanticipated scenarios. In real-world deployments, vehicles encounter a diverse range of operational states, such as varying road gradients, speed zones, any of which can

change the underlying data distribution and undermine detection accuracy if not properly accounted for during training. This limitation in transferability directly undermines the resilience of CPS, as it prevents systems from maintaining high detection accuracy when exposed to novel conditions. From a resilience perspective, adaptability is essential. Systems must be capable of not just identifying anomalies under known conditions but also responding effectively when entering previously unseen environments. The inability to do so can lead to a surge in FNs and FPs, or, more dangerously, complete system failure. To enhance resilience, modern detection frameworks must integrate continuous learning, domain adaptation, or transfer learning techniques (Rajapaksha et al., 2023). These strategies enable models to update themselves using new data encountered during operation or leverage knowledge from related domains to maintain robustness. Integrating such flexibility into detection architectures, systems can better absorb shocks, operate effectively across changing conditions, and ensure sustained safety and reliability for resilient CPS design.

5.10 Back Up or Safe Mode Needed

As shown in the referenced simulations, even after an anomaly is correctly identified, the system's ability to maintain operational continuity depends on what actions are taken next. Without a built-in fallback mechanism or safe mode controller, the system may still collapse or require manual intervention, which undermines the very purpose of autonomous resilience (Liu & Wang, 2021). A safe mode acts as a protective layer that the system defaults to when anomalies are detected, ensuring that core safety parameters are upheld regardless of anomaly type or severity. Designing for fail-operational behaviour, resilient VCPS architectures increasingly incorporate fail-operational control schemes that allow vehicles to continue functioning under degraded conditions. These may include pre-programmed emergency behaviours, redundant control logic, or switching to more conservative control parameters post-anomaly. Thus, integrating fallback control systems is essential to transition from anomaly aware to resilient.

5.11 Need for Strategic Policy Implementation

The need for robust policy is evident as cyber-physical resilience encompasses technical concerns requiring strategic regulation for low-resource SIDS. Under constraints of infrastructure fragility and limited redundancy, this amplifies the impact of disruptions, detection latency, containment delay, and recovery duration metrics, which can serve as actionable indicators that need to be monitored and enforced. These metrics allow transport authorities and mobility regulators to assess system robustness quantitatively, supporting informed investment, risk assessment, and incident preparedness planning. For example, a resilience audit framework built on these indicators could be used to grade readiness across vehicle fleets, evaluate vendors' control systems, or mandate minimal safety performance under anomalous conditions. Strategic policies will need to define minimum performance thresholds and outline enforcement measures for performance metrics or require built-in fallback mechanisms for certified autonomous platforms. In SIDS, where infrastructure investment must be prioritised carefully, embedding such metrics into procurement or regulatory standards ensures long-term system sustainability, reduces vulnerability to cyberattacks or faults, and promotes public confidence in intelligent transport deployments.

Conclusion

This study addressed a persistent gap in the CPS security literature where most work develops and benchmarks individual detection algorithms in scenario-specific settings but seldom explains how those results translate into resilience outcomes. Using an archetypal CPS tightly coupled to transportation critical infrastructure vehicle platooning, this work adopted evidence first approach, a representative supervised AD method was applied in a realistic case study, and the empirical results were used to produce a coherent set of AD-informed design considerations for CPS resilience. The contribution explicitly maps detection performance to resilience outcomes, consolidating insights usually scattered across separate publications into a single, operationally framed set of considerations to drive concrete CPS design choices. While not exhaustive, the set provides a concise guide to

what should be prioritised when integrating AD modules in CPS. These guidelines are particularly pertinent to SIDS, where thin operational buffers, intermittent connectivity, and longer restoration timelines can be further exacerbated if design considerations are not adequately addressed. This guidance can also aid engineers, operators, and policymakers in specifying, procuring, and deploying resilient CPS, especially in SIDS, moving the discussion from benchmark accuracy to maintained service, safe recovery, and sustained societal value.

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Amir MOHAMMED is a PhD Student at the University of the West Indies. B.Sc.(e) in Electrical and Computer Engineering and MSc in Electrical and Computer Engineering from the University of the West Indies. Research interests include Fuzzy Systems, Resilient Control, Artificial Intelligence and Cyber Physical Systems.

ORCID ID: <https://orcid.org/0000-0001-9420-1601>

Daniel GOITIA is a PhD candidate in the Department of Electrical and Computer Engineering at The University of the West Indies (UWI), St. Augustine. His research interests focus on wireless communication, with emphasis on 6G networks, the Internet of Things (IoT), and cybersecurity. He is passionate about advancing secure, efficient, and scalable communication technologies for the future digital landscape.

ORCID ID: <https://orcid.org/0009-0001-6737-9567>

Sheikh AHMAD is a SCADA Supervisor in the municipal water and wastewater industry in Ontario, Canada with a M.Eng. in Electrical and Computer Engineering specializing in Robotics and Controls from Western University, London, Ontario, Canada. Research interests include Industrial SCADA/Automation and Operational Technology Cyber Security.

ORCID ID: <https://orcid.org/0009-0003-7983-0292>

Craig RAMLAL is the Executive Director of the Artificial Intelligence Innovation Centre (AIIC), at the UWI and the Head of the Control Systems Group in the Department of Electrical and Computer Engineering, Faculty of Engineering, at the University of the West Indies, St. Augustine.

ORCID ID: <https://orcid.org/0000-0002-0960-528X>

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STATE TERRITORY AND POWER RELATIONS IN SOUTH AFRICA: NATIONAL UNITY OR OLIGARCHY GOVERNMENT FIEFDOMS?

Johannes Tsheola

University of South Africa, South Africa

E-mail: johannes.tsheola@gmail.com

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Abstract. This article argues that South Africa's 2024 Government of National Unity (GNU) re-institutes elite democracy for political incumbency self-preservation in favour of the African National Congress (ANC) and president Ramaphosa. Historically, the ANC appropriated state territory as personal presidential and party fiefdoms, to leverage state and political power, while eroding democracy, accountability, rule of law and the universality of freedoms. The article theorises elite democracy and conceptualises "state idea" to reveal that the universality of freedoms, necessary for national unity and stability, is not a natural right, and thus disambiguates South Africa's hasty GNU. Consistent with Hegel's philosophy of freedom and Nkrumah's consciencism political ideology, the article distils elitist characteristic features of the GNU that exude political incumbency self-preservation. Methodologically, the article conducts desktop literature review, analytical conceptualisations and evaluation of South Africa's contextual politics for the hastily established GNU. The article finds that the GNU re-institutes elite democracy through a fictitious 71.75% majoritarian politics, thereby appropriating state power, "state territory" and GNU member political parties to repurpose them as the ANC's fiefdoms for regeneration of political power in service of party political tenure and presidential incumbency self-preservation, while shirking accountability and the rule of law. Therefore, the article concludes that this GNU undermines national unity and stability. The article recommends that national unity and stability require a "state idea" founded on obedience of the nation-state's laws and the universality of freedoms for all South Africans as equals.

Keywords: power relations; freedom; state idea; state territory; oligarchy government; South Africa

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1. Introduction

The dawn of South African democracy was heralded through a GNU, based on a predetermined criterion that includes parties with a minimum of 10% of the 1994 national vote, when reconciliation, national unity and stability were primate (Tony, 2025; Tsheola, 2025). Post-1996, though, the ANC exploited its majoritarian politics to institute elitist democracy, misrule and divisiveness, which epitomised democratic South Africa's 30-year history (Heller, 2020; du Toit, 2024). As Booyesen (2011: 359) and Sebola & Tsheola (2024: iii) observe, the ANC historically repurposed "state territory as personal-organisational fiefdoms" for presidential and political leadership incumbency self-preservation, rather than for national consciencism of the universality of freedoms. Effectively, South Africa's 30-year democracy involved oligarchy government where power rested with fascists, consisting of individuals, families or corporations, characterised by wealth, privilege and social status, hereafter described as oligarchs. Ironically, one year of the 2024 GNU, purportedly founded on national unity and stability, attracted heightened threats of coups (Khumbudzo Ntshavheni, Minister in the Presidency, public statement on July 14, 2025, cited in Sicetsha, 2025). The national intelligence revelation that the nation-state is now facing

“rising threats to state stability,” include “illegal migration, espionage, organised crime, cyber threats,” public safety and economic sabotage (Sicetsha, 2025), makes mockery of this GNU. According to Kroeker (2022: 122), African national unity and stability “are made and broken due to disruption, a crisis of tradition, a lack of identity and a confrontation with globally circulating, competing models of modernity.” Africa citizens continue to wait for liberation and freedoms (Obicci, 2025). This article theorises “state idea” of national unity and stability using Hegel’s (1894) philosophy of the universality of freedoms and Nkrumah’s (2008) concept of consciencism to argue that South Africa’s 2024 “GNU Brand” is a bane of the nation-state’s democracy because it re-institutes elite democracy for political self-preservation by regenerating “state territory” as the ANC’s and Ramaphosa’s personal presidential fiefdoms.

Whereas the ANC’s 30-year misrule exploited political majority to entrench elite democracy, the 2024 GNU reproduces a 71.75% fallacious majority to re-install elite democracy in service of the ANC’s re-invention of state power abuses, appropriation of political power from state territory, extension of party tenure and protection of presidential incumbency. The hasty, now rocky, GNU equally undermines the universality of freedoms, accountability and rule of law. According to Hegel (1894), freedoms are collective because individual freedoms are validated by universal freedoms wherein all citizens, including commanders of the nation-state, equally obey the laws. The nation-state does not exist *ex nihilo*; instead, it requires all citizens’ adhesion to its statehood and obedience of its laws (Hegel, 1894). Therefore, the nation-state is “the very foundation and framework of collective freedom,” because freedom is “neither the mere consciousness of an absence of necessity nor the physical manifestation of some inner desire” nor a natural right (Hegel, 1894: n.p.). Commanders of the nation-state must be servants of the Constitution, just as the rest of society; and, this “state idea” is crucial in national unity, and universality and particularity of citizens’ collective freedoms. South Africa’s democracy is founded on “state idea” ideals of the universality of freedoms, accountability, rule of law and unity in diversity (RSA, 1996). Philosophically, therefore, GNU elite democracy proscribes “state idea” ideals in reverence for political self-preservation.

Most African democracies are attendant to elite politics, misrule, unfreedoms, presidential incumbency self-preservation and corrupt patronage (Fagbadebo, 2019; Moti, 2019; Fagbadebo & Dorasamy, 2021; Engels, 2022, 2023; Obicci, 2025). South Africa’s 30-year version of state capture and corruption too are extensively codified (Booyesen, 2011; Isike & Onapajo, 2017; Croucamp & Malan, 2018; de Klerk & Solomon, 2019; du Toit, 2024). Answering questions at the State Capture Commission, president Ramaphosa claimed that he remained in Zuma’s Administration “as a principled act of ensuring” that state capture is ultimately defeated and its damage “less devastating” (Zondo, 2022). Since ascending to state presidency in February 2018, though, Ramaphosa presided over state power as “an act of ‘regenerating’ political power for the present (ANC elites) cohort,” to borrow Booyesen’s (2011: 360) framing, repurposing “state territory” for state capture continuities. Also, Ramaphosa admitted in August 2020 that the ANC is accused number one in South Africa’s corruption (Bloomberg, 2020; Cohen, 2020). Recently, Prince Mashele characterised Ramaphosa as the “criminal in chief” heading a criminal enterprise (Ntanzi, 2025). The ANC’s 30-year governance indiscretions are systemic to former liberation movements in African democracies (Isike & Onapajo, 2017; Moti, 2019; Mbandlwa, 2023; Mlambo, Masuku & Mthembu, 2024; Okorie, 2024; Onyango, 2024; Obicci, 2025); and, the GNU’s and/or DA’s “civilising missions” will fail. Indeed, the GNU entangles other political parties, especially the DA, in the ANC’s internal rivalries, succession battles, abuse of state power, regeneration of political power and protection of Ramaphosa’s presidential incumbency. During the 2024 electioneering, Ramaphosa described the DA’s “national flag burning” campaign advertisement as treasonous; and, the DA was steadfast the ANC is a corrupt enterprise and that Ramaphosa should be held accountable for the Phala Phala scandal. Ironically, Ramaphosa’s ANC and Hellen Zille’s DA forged a hasty GNU in June 2024. Paradoxically, voters seem to have responded to the DA’s electioneering messaging, punishing the ANC by an unprecedented haemorrhage of 17.3% of the national vote (Tsheola, 2025). Apparently, the DA lost consciencism of the “state idea” ideals and handed “state territory” back to the ANC, embracing state capture continuities and the ANC’s protection of Ramaphosa’s presidential

incumbency for political patronage, describing the Phala Phala saga as “irrelevant.” The 2024 GNU’s and DA’s complicity in undermining accountability and rule of law is palatable.

This article, therefore, borrows from Louis D. Brandeis’ (US Supreme Court Justice cited in Albright, 2018: 10) framing, to assert that this GNU government “is the potent, the omnipresent teacher” that “teaches people by example” and “a law breaker” that “breeds contempt for law,” inviting every person to become law unto themselves. The GNU’s unprincipled politics created government that is characteristically rocky, fractuous, incoherent and dispute-riddled (Haffajee, 2025a; Seepe, 2024a), teetering on the brink of normalising the ANC’s misguided “divisibility” of freedoms (Heller, 2020; du Toit, 2024; Balton, 2025). Public trust in this GNU is already decimated (Haffajee, 2025a). The DA’s complicity in GNU state capture continuities and the multiplicity of ANC splinters’ political personality cults, inclusive of Ramaphosa’s fractuous ANC, are a cause of great distress and annoyance for South Africa’s democracy, national unity and stability. This GNU elite democracy entangles the DA in the ANC’s abuse of “state territory” and leveraging of state power and national governance for regeneration of political power, extension of party tenure and presidential incumbency self-preservation, subverting democracy, accountability, rule of law and the universality of freedoms.

2. Theorising Freedoms and Democratic “State Idea” Ideals

Freedom is not a “natural right;” instead, it is intricately intertwined with the “state idea” and its politics structure the substance and functions of democracy. Ontologically, the distinctness of human self-consciousness from the natural world suggests that freedom is the sense of being autonomous, rational and self-determining (Hegel, 1894; Bowman, Malherbe & Suffla, 2024). Hence, the creation of a modern state as the political and legal embodiment of people’s spirit is one of the three stages of the evolution of freedoms (Hegel, 1894). As the primate foundation and framework of collective freedoms, the nation-state requires obedience of its laws by commanders of the state and citizens alike, as servants of the Constitution (Hegel, 1894). That is, the morality of freedoms’ “universality and particularity” only finds realistic expression within national ambiances of equal obedience of the nation-state’s laws, wherein collective public, rather than individual, good takes precedence within strict confinement of civic freedoms. Individual freedoms are, therefore, validated through universal freedoms wherein all citizens equally obey the nation-state’s laws. This “state idea” of the nation-state being the “foundation and framework” of the universality of freedoms is both a necessary and sufficient condition for national unity. Therefore, the authentic citizen actively promotes public interest to realise own nature as an agent of universal freedoms and to source happiness, which is the best possible exercise of individual freedoms (Hegel, 1894). As Hegel (1894: n.p.) puts it, “the state is actual, and its actuality consists in this, that the interest of the whole is realised in and through particular ends.” Crucially, the “state idea” ideals are “won through an infinite (treacherous historical) process of the discipline of knowledge and will power,” wherein “each period is involved in such peculiar circumstances, exhibiting a condition of things so strictly idiosyncratic, that its conduct must be regulated by considerations connected with itself, and itself alone” (Hegel, 1894: n.p.). States fail their original mission and lose *raison d’être* when citizens’ general public political aims and oligarchs’ personal individual aspirations are incompatible. South Africa’s formal transition from apartheid to democracy signified triumph of “hope over despair” (Bowman et al., 2024), with hyperbolic liberation dividends expectations. Thirty years later, South Africa’s “liberatory praxis,” “global well-being,” equity, justice, inclusivity and freedoms are convoluted (Bowman et al., 2024; Ragolane, Thusi & Khoza, 2024).

2.1. The Concept of Consciencism

Nkrumah’s (2008) consciencism political ideology calls for philosophical framing that addresses African societies’ social and political-economy injustices, attendant to disharmony among three distinct African consciousness perspectives, viz.: *Abstract Liberalism*; *Social Structure (Standing or Status) as a Basis for Rights*; and, *Ordinary Africans’ Lived Experiences*. Consciencism seeks to unify these perspectives in order to foster collectivism, inclusivity, shared ownership of futures, universality of freedoms and unity. Therefore, the empirical

test of desirability of democracies' moral foundations rests on national consciencism "state idea" ideals of unity, inclusivity, collectivism, universality of freedoms and shared ownership of futures. Overall, African democracies consist of divisive politics, misrule, political incumbency self-preservation and "democratic" authoritarianism (Fagbadebo, 2019; Moti, 2019; Heller, 2020; Fagbadebo & Dorasamy, 2021; Engels, 2022, 2023; du Toit, 2024; Onyango, 2024; Obicci, 2025), rather than "true democratic thinking" and visions (Kroeker, 2022). Consciencism "state idea" entails universality of freedoms, transparency, accountability and rule of law that create "national unity futurity." However, African oligarchs assert decisive voice and power on nation-states' "planetary futures" (Ede, 2016; Sarr, 2019; Kroeker, 2022; Obicci, 2025) devoid of consciencism "state idea" ideals. These oligarchs uniformly fail to constitute sets of democratic dispositions, aspirations, intentions and practices, consistent with the universality of freedoms. Instead, they hold skewed ideas of collectivism and freedoms, portraying themselves as guardian angels and vanguards, rather than experimental avant-gardes (Moti, 2019; Mbandlwa, 2023; Obicci, 2025). Generally, African oligarchs appropriate state power and national governance for sectional interests and privileges, corrupt patronage and incumbency self-preservation (Ede, 2016; Isike & Onapajo, 2017; Moti, 2019; Mbandlwa, 2023; Mlambo, Masuku & Mthembu, 2024; Okorie, 2024; Onyango, 2024; Obicci, 2025). Inevitably, African democracies are generally characterised by selective obedience of nation-states' laws, rendering freedoms divisible and coups as popular resets for democracies.

2.2. Democratic State, Governance Power Relations and Freedoms

Whereas state power was traditionally created by states, modern democratic architectures reproduce state power through governance and command by non-state actors (Keping, 2018; Kadri, 2023; World Future Fund, 2023). As political systems, democracies do not automatically safeguard power relations equities and the universality of freedoms, because governance is not neutral nor organically interconnected with democracies (Tsheola, Sebola & Mamabolo, 2023). Post-World War II democratic governance power relations were globally mediated by transnational capitalism and corporatism ideology in favour of non-state actors (Pinto, 2017; Christiansen, 2020; Pasetti, 2023). Christiansen (2020) frames corporatism as the third greatest political ideology of modern societal organisation meant to incorporate society's diverse economic interests by creating representative political positions for pluralist democracies. Even Rexford Tugwell, an economist in former USA president Franklin Roosevelt's Administration, was envious of the corporatist state order, famously stating that it was the cleanest and most effective state (cited in Pasetti, 2023). However, transnational hybridisation of corporatist institutions and celebration of the corporatist state as milestones for democratic governance in the world (Kadri, 2023; Pasetti, 2023) failed to produce pluralist democracies nor foster universal freedoms. Instead, modern corporatism legitimised "Fascism even in democratic circles," creating corporatist states with non-state commanders asserting decisive power and dominion over society (Pasetti, 2023: 747). Therefore, democratic governance nation-state power, the primate legal source of the state's unique right to control its juristic territory, subordinated nations to command of oligarchy governments (Kadri, 2023). Consequently, the modern nation-state as the institution of society's formal politics achieved weak nominal juristic victory over territorial space without consolidating independence and sovereignty, thereby becoming "inadequate" and "available to be manoeuvred" (Kadri, 2023). Paradoxically, democratic governance's minimalist state asserted vibrant activism, ceding control of the nation-state power to the command of secretive oligarchs (Pinto, 2017; Christiansen, 2020; Kadri, 2023; Pasetti, 2023; Tsheola et al., 2023), thereby shirking the universality of freedoms.

Modern democratic governance, therefore, does not equate to universal human rights nor freedoms nor fairness nor justice across the world, especially in Africa (Onyango, 2024; Obicci, 2025). The post-1990s global pre-eminence of state democratic governance and ascendancy of fascist corporatism created democratic states with venality to fascist capture (Pinto, 2017; Christiansen, 2020; Kadri, 2023; Pasetti, 2023; Obicci, 2025). Consequently, modern democratic states are generally weak, without real power for command of national politics, becoming totalistic law and order institutions reliant on coercion for enforcement of undemocratic decisions and exertion of unconstitutional dominion over society. Paradoxically, modern democratic states have caused the greatest destruction of life, surpassing the Permian Extinction, reported to have occurred over 252 million years

ago, killing about 90% of “all life on earth,” consisting of 95% and 70% of marine species and terrestrial life, respectively, in a period of 20 000 to 15 million years (Kadri, 2023; World Future Fund, 2023; Britannica, 2025). Indeed, the modern world is attendant to uncertainties, widespread “toils and snares,” confrontations and extensive “protests and conflicts,” because commanders of nation-states’ powers are goaded by “lunatics” (Pinto, 2017; Albright, 2018; Engels, 2022; Kadri, 2023; Pasetti, 2023; World Future Fund, 2023). Africa’s modern democracies too are associated with greed and fascist tendencies (Obicci, 2025), exposing citizens to divisiveness and injustices. Therefore, Africa’s democratic state governance remains inordinately imprudent, ineffective and bad (Tsheola et al., 2023).

To enforce universality of freedoms, state governance has to be embedded with six democratic principles, viz.: legitimacy, transparency, accountability, rule of law, responsiveness and effectiveness (Keping, 2018; Tsheola & Sebola, 2018). Accountability and the rule of law, in particular, have to apply equally to citizens and oligarchs alike. Prudent democratic state governance, therefore, maximises national consensus, shared values, public consent and citizen approval of civic affairs. Therein, accountability and the rule of law are supreme and their primary goal is to “regulate” citizens’ and nation-state commanders’ conduct alike, manage public affairs and maintain order, while protecting basic political rights, freedoms and equality (Tsheola & Sebola, 2018). Democratic governance majoritarian rule and winner takes all principle should, therefore, ensure that government exercises, in Keping’s (2018: 3) words, “authority to maintain order” and “to guide, steer and regulate citizens’ activities through the power of different systems and relations,” maximising public interests and the universality of freedoms. Thus, the political-economy of democratic state governance entails nation-state activism and lawful enforcement of obedience of laws by all citizens and oligarchs as equals (Tsheola & Sebola, 2018), in order to guarantee the universality of freedoms. Democratic governance means that the nation-state has to exercise authority and power, in trust on behalf of the people, by coordinating compliance with “state idea” ideals among multiple centres of power to foster the universality of freedoms.

2.3. Elite Democracy and Regeneration of Political Power

The long history of theorisations of democracy (Cunningham, 2002; Shapiro, 2003; Held, 2006; Christiano, 2008; Dryzek & Dunleavy, 2009; Keane, 2009; Pinto, 2017) has not exhausted the full spectrum of democratic thought and scope of democratic theory (Laurence, 2018). Beyond conceptions of the meaning of democracy, democratic theories discuss moral foundations, obligations, obedience of rules, challenges and desirability of alternative democracies. Broadly, there are three categories of democratic theories, viz.: normative, empirical and conceptual (semantic) theories. Normative theories examine democracy’s moral foundations and desirability, empirical theories test pragmatism, substance and functions of democracies, while semantic theories formulate and interrogate meanings of the concept of democracy (Keane, 2009; Laurence, 2018; Pasetti, 2023). This subsection evaluates desirability of elite democracy’s moral foundations using consciencism “state idea” ideals of universality of freedoms and national unity to reveal that it serves oligarchs’ political self-preservation.

Etymologically, democracy is a “process of collective self-rule,” consistent with its Greek origins from *demos* and *kratos*, meaning “the people, the many” and “to rule,” respectively (Cunningham, 2002; Shapiro, 2003; Held, 2006; Christiano, 2008; Keane, 2009). Broadly, democracies are classified into three categories, viz.: participatory; pluralist; and, elitist (Laurence, 2018; Pasetti, 2023). Participatory democracy involves citizens directly in decision-making and governance, pluralist recognises organised associations’ representation of diverse interests and opinions in society, while elitist refers to a competitive electoral system among elites who are in return supposed to be accountable to the people (Laurence, 2018; Pasetti, 2023). Elite democracies manifest through liberal majoritarian or coalition politics, and are venal to state and political power abuses and shirking of accountability and rule of law. Liberal elitist democracies’ “expression and fundamental principles” of political parties’ electoral contestations, majority rule and winner takes all, vest governmental power in one party (Held, 2006; Laurence, 2018; Pasetti, 2023). With these principles, ruling parties systematically and substantively abuse power to violate democratic norms and invalidate people’s participation and/or representation in decision-making

and governance (Ajei, 2016). These principles accord unconstitutional governmental power to a single political party that mutes public discourse and perverts public affairs pluralism. Hence, there are authoritarian politics enclaves within liberal elitist democratic polity (Ajei, 2016) that hollow socio-political and economic pluralism. According to Ajei (2016: 445), Africa's elitist democracies lack "representation and participation of citizens in democratic processes and institutions" because they vest state and political power, and the exercise thereof, in the majority parties to the exclusion of the people. Unsurprisingly, regular "elections in Africa have become recurring sources of violence and deception" rather than reservoirs of "genuine political pluralism" (Ajei, 2016: 453). South Africa too has endured liberal elitist democratic politics under the ANC's 30-year misrule.

With majority rule winner takes all principle, political parties' electoral contestations "fracture rather than unite political action towards a common (national) goal," thereby fostering societal conflicts and rigid contrasting exclusivities as integral aspects of nation-states' democratic practices (Ajei, 2016: 449). Thus, "the exclusive appropriation of power by a successful party at elections" degenerates into "life and death struggles among contending parties," repurposing parties into "machines for the conquest of power" (Ajei, 2016: 450). Hence, elitist democracies are riddled with hostilities, unhealthy rivalries and insatiable thirst for private money, the primate lubricant for political insensibilities, incivilities and instabilities (Tsheola, 2025). Elite democracies concentrate state and political power in presidencies and oligarchs, perverting democratic norms and government legitimacy (Ajei, 2016). Devoid of ethical morality and universality of freedoms, elitist democracies foster divisiveness, disunity, public distrust and subversion of voters' suffrage power (Ajei, 2016; Pasetti, 2023; Tsheola, 2025). Similarly, where elections do not produce majoritarianism, political parties often adopt coalition politics to create artificial majoritarianisms and institute elitist democracies for political self-preservation, disguised as national unity.

Elitist democracy, majoritarian or coalition-based, derails evolution of the consciousness of the universality of freedoms. It readily repurposes state territory into personal presidential and party fiefdoms for appropriation of state and political power. Even self-professed democrats and anti-fascists ultimately entrench widespread suppression of the universality of freedoms under elitist democracies (Pinto, 2017; Albright, 2018; Christiansen, 2020; Pasetti, 2023; Obicci, 2025). Essentially, elite democracy has venality to incompetence, corruption and power abuses that violate precepts of "conventional political wisdom" (Albright, 2018; Pasetti, 2023; Onyango, 2024; Obicci, 2025), thereby perverting accountability, rule of law and universality of freedoms. Thus, public violence and civil strife, military coups and forceful seizure of state power have become enduring popular resets for elitist democracies (Fagbadebo, 2019; Fagbadebo & Dorasamy, 2021; Engels, 2022, 2023; Okorie, 2024). Concomitantly, coalition-based elitist democracies hollow state power, enfeeble democracy as well as shirk accountability, rule of law, inclusivity, universality of freedoms and national unity. In pursuit of their compulsive greed, oligarchs rush to coalition governments in order to assure themselves of continued assertion of decisive unconstitutional powers by weaponising law against democracy, silencing dissent, subverting the universality of freedoms and regenerating political power (Simakoloyi, 2025).

3. South Africa's 2024 GNU Oligarchy Government

The ANC's historical profoundness as Africa's oldest liberation movement is paramount, but it is the youngest as a ruling party (Booyesen, 2011; Isike & Onapajo, 2017). The party's 30-year national governance involved conflation and fusion of party and state, incompetence, corruption, misrule, murder of the nation-state and omnipotent intra-party rivalries and factionalisms (Booyesen, 2011; Du Toit, 2024). As ruling party, the ANC had the opportunity to leverage state and political power for consolidation of multi-party democracy; instead, it appropriated state power to institute elite democracy in service of executive political leadership and presidential incumbency self-preservation, corruption and patronage (Booyesen, 2011; Croucamp & Malan, 2018; De Klerk & Solomon, 2019; du Toit, 2024). Consequently, "the liberation dividend" was "diluted" and National Democratic Revolution (NDR) ideals deferred (Booyesen, 2011; Isike & Onapajo, 2017; Du Toit, 2024). ANC's electoral

politics and winning degenerated into existential struggles for abuse of state power, institutional capture, hollowing of democratic institutions and hobbling of state performance (Booyesen, 2011; Croucamp & Malan, 2018; De Klerk & Solomon, 2019; Du Toit, 2024). Also, intra-ANC rivalries, factionalism and succession battles were transposed into contestations for the exercise of direct political power over the state and repurposing of “state territory” into “personal fiefdoms” for party and presidential incumbency self-preservation (Booyesen, 2011; Du Toit, 2024). Effectively, the ANC appropriated state power to reward oligarchs and prolong tenure of presidential incumbency and party command of the state, while simultaneously subverting democracy. Under the 2024 GNU, ANC intra-party rivalries, personality cults factionalisms and divisiveness remain prevalent, with state territory as the primary contestation site, including the judiciary and democracy-supporting institutions.

Disambiguation of the GNU as greedy immoral elitist democracy disguised as national unity is “the truth of necessity,” because the ANC is using the GNU to leverage state power and national governance to “regenerate political power” for self-preservation, intra-party rivalries and succession battles. Hence, the ANC’s parliamentary chief whip, Mdumiseni Ntuli, intimated that it would be “the end of the movement” if the DA Cabinet power bloc “defy the President’s direction” amidst an upcoming ANC conference, because of the ANC’s deep-seated “irritation” with the DA (cited in Haffajee, 2025b). This GNU is, therefore, patently democratically incompetent and corrupt, because it subverts accountability and rule of law in service of political self-preservation, while suppressing dissent as anti-constitutionalism and weaponising law against democracy (Simakoloyi, 2025). Complicitly, the GNU bandwagon shirks accountability in favour of the nation-state’s commanders, rendering government a potent omnipresent law breaker that “breeds contempt for law,” teaching citizens to become law unto themselves. Effectively, this GNU extends the ANC’s tenure of corruption, lies and cover-ups, deceit and subterfuge, misrule and state capture (Boesak, 2023). Unsurprisingly, this GNU’s politics are impeachable modern geopolitical neologism disguising elitist democracy as national unity, riddled with divisiveness that undermines the universality of freedoms, accountability and the rule of law.

3.1. The 2024 GNU Founding Narratives: National Unity and Stability

Beyond the deceptive rhetoric of national unity and stability, the GNU insulates the ANC and Ramaphosa from the pain of voters’ assertion of suffrage power. Elite democracy is incongruent with universal freedoms and national unity. Also, the rocky GNU was determined exclusively by ANC, DA and business elites, defying constitutional democratic principles. Proponents of the GNU suggest strangely that voters determined that there should be a unity government, while castigating dissent as anti-constitutionalism. South Africans did not vote for this impeachable GNU elitist democracy which rejects parties with between 9.5% and 14.5% vote share, only to accommodate those with 1.5% or less. That is, the GNU recklessly castigates 24.1% of MK Party and EFF, third and fourth largest parties, respectively, voters as anti-constitutionalists. The truism is that Ramaphosa (ANC), Steenhuisen (DA), Zuma (MKP) and Malema (EFF) have incongruous egotist political differences and cultist personalities, and South Africans are subjected to their deceptions. Also, Ramaphosa and Steenhuisen assert decisive state and political power calling for national unity while simultaneously preaching linear ideologies of divisiveness. Hence, GNU elite democracy is devoid of national unity and universality of freedoms consciencism; instead, it serves politicians.

Far from national unity and stability, Ramaphosa publicly told ANC followers at the January 08th Anniversary and Lekgotla, respectively, that “the ANC is still in charge” and the GNU exists to implement the ANC’s NDR (SABC, *Current Affairs*, January 11 & 25, 2025). Conversely, Steenhuisen (2025) recounts that the DA was in the GNU “to share power” rather than “make up numbers” for the ANC to roll out its policies. Also, Steenhuisen (2025) believes that the ANC has publicly disrespected its GNU partners, undermining mutual coalition government trust. The leader of Patriotic Alliance (PA) and GNU minister, McKenzie, too “questioned where the unity was” when GNU partners learn about the signing of bills from media (cited in Payne, 2025). Ironically, it is through the DA’s complicity that the GNU controls 287 (71.75%) seats in the National Assembly (NA), while opposition holds 113 (28.25%) seats (Tsheola, 2025), allowing the ANC to conduct governance with disdain, as if

it held outright electoral majority. The true motive for this GNU remains a secret of oligarchs, while citizens endure confusing governance politics with non-unitary and incoherent GNU diplomacy and ever present threats of collapse. This GNU's disunity and diplomatic incoherence permeate South Africans' daily experiences, thereby eroding public trust and reproducing the nation-state's epistemic and omnipresent fractures, rendering national unity and stability narratives impeachable. Ironically, when Ramaphosa assumed state presidency in February 2018, the nation-state was ravaged by state capture (Croucamp & Malan, 2018; de Klerk & Solomon, 2019; Zondo, 2022; du Toit, 2024), whistleblowers assassinated and society starkly divided (Heller, 2020; Gcabashe, 2023; Tsheola et al., 2023). However, Ramaphosa did not envision national unity government then. The 2019 ambience of divisiveness too could not prompt Ramaphosa to envision national unity government because the ANC secured 57.5% majority in the NA (Tsheola, 2025). Under Mandela's leadership, the ANC won 62.7% majority and conceived the 1994 GNU. For Ramaphosa, national unity and stability only became necessary when the ANC haemorrhaged 17.3% of national votes in 2024. Ramaphosa only repurposed himself as the nation-state's guardian angel and saviour in response to electoral pain. Thus, this article highlights hidden motives for this GNU, beyond the national unity and stability deception, to expose abuse of state power and state territory as personal fiefdoms for political self-preservation.

Historically, abuse of state territory as personal presidential incumbency fiefdoms defeats accountability and rule of law, facilitating democratic resets and onset of vicious circle of coups, sham elections and civil strife. This selective GNU squanders prospects of national unity on four grounds, viz.: The majority of South African voters are poor and traditional constituents of the ANC, whose splintering is causing disunity among Blacks; The ANC's historic decline in electoral fortunes was caused by its splintering, leaving 105 (28.25%) of the 2024 NA seats shared among six (6 of the 18) political parties, largely supported by Blacks, outside the GNU; The second (MK Party) and third (EFF) largest parties in the 2024 NA, consisting of 92.38% (97) of the 105 seats held by ANC splinters, are ANC's personality cult-based breakaways, with palpable dislike of the ANC's Ramaphosa faction; and, Only two parties outside the GNU, Build One South Africa and ActionSA, with a total of 8 seats in the NA are by their origin associated with the DA. Therefore, the fissures that the GNU needs to paper-over for national unity and stability involve ANC's fragmentation of black constituencies, consisting of 81.4% of South Africa's 2025 population (RSA, 2025). The DA is adamant that it does not want the EFF and MK Party (a total of 97 NA seats) in the GNU; similarly, the two parties dislike the DA and FF Plus. Any concept of national unity would be fallacious if it excludes 24.1% (EFF and MK Party) of the 2024 voters from the GNU just because the DA does not want them or worse, due to their rejection of Ramaphosa's presidential incumbency. Equally, a GNU that excludes 93 (23.25%) NA seats (DA, 87 and FF Plus, 6) just because the EFF and MK Party dislike them, is impeachable on national unity and universality of freedoms consciencism.

South Africa is in the grip of divisiveness as constitutional freedoms are incrementally meaningless for many, amidst GNU government being the omnipotent law breaker shielding oligarchs from accountability. SABC reporter revealed that unnamed business leaders wrote a letter to the ANC and the DA warning them that the DA must not be removed from the GNU, following the DA's voting against the GNU's fiscal framework on April 02, 2025 (*SABC, Current Affairs, The Agenda*, April 06, 2025). According to Ramaphosa, government and the ANC make "own decisions" based on considerations for the advancement of people's interests (Nozulela, 2025). Ramaphosa argued, deceptively, that the ANC is influenced by people, rather than business pressure (Nozulela, 2025). If Ramaphosa's assertions were true, there would have been no deceptive GNU after the 2024 elections because there was no referendum on the GNU. Also, the ANC itself, seeing its poor electoral performance of only 40.2%, did not consult with its own constituencies nor tripartite alliance partners. Instead, ANC political elites adopted the GNU in haste. Whereas Ramaphosa said that business does not dictate government nor his ANC decisions (Nozulela, 2025: n.p.), his own ascend to the party and state presidency was supported by secretive private money sealed by court of law. Having gained state presidency through party presidential campaign shrouded in controversy, Ramaphosa would not have weaponised law to deny the public access to his private funders. Effectively, the secretive business elites' call for the ANC not to remove the DA from the GNU is self-

preservationism intended to prevent potential ANC splinters' reconciliation. Equating national unity and stability with ANC/DA unity is deceptive. Ntuli too expressed "some discomfort" because of business elites' "partisan considerations" undertone that "the state cannot be trusted and that it would have no capacity without the DA" (cited in Haffajee, 2025b: n.p.). The DA too believes that "a government without the DA would have dire consequences for the country's economy" (Nozulela, 2025: n.p.). The notion of national unity being equated with the ANC/DA unity is incongruent with South Africa's "state idea" of democratic constitutionalism, inclusivity and universality of freedoms. Also, patriotism is not equivalent to the unity of Ramaphosa's ANC faction and the DA. Hence, this ANC-led and DA-controlled GNU is rocky with deleterious divisiveness and government incoherence.

3.2. Accountability, Rule of Law and Universality of Freedoms

South Africa's Constitution envisions a nation-state based on rule of law, accountability and freedoms for all citizens as equals (RSA, 1996); however, the ANC's 30-year misrule decimated this vision. As Balton (2025: n.p.) puts it, "One of the biggest tramplets of freedom is the immense misinformation and disinformation that goes on daily," denying citizens "the ability to make informed decisions and, more dangerously," normalising falsification of facts. The ANC governments, and now the GNU, do "not respect the dignity" of citizens nor the universality of freedoms (Balton, 2025). Hence, Seepe (2025c) characterises Ramaphosa's February 2025 GNU State of the Nation Address (SONA) as "more 'promises and lies'" that fuel public anger over "failing leadership." Besides Ramaphosa's Phala Phala saga, serious corruption allegations are made against six ANC GNU Cabinet ministers, including deputy president, suggesting that state capture is the ANC's enduring modus operandi, rather than "an anomaly" associated with the Zuma Administrations (SAT-International, 2025). Notwithstanding the DA's rhetoric, the GNU is complicit in state capture continuities and Ramaphosa's shielding of oligarchs from accountability and obedience of the nation-state's laws. In return, the DA's and GNU's entanglement in the ANC's abuse of state territory and power serves Ramaphosa's presidential incumbency self-preservation and shirks accountability and the rule of law. On May 16, 2025, Ramaphosa conceded that "true freedom is still distant" for South Africans (SABC, *Current Affairs*, May 17, 2025). Historically, the ANC systematically betrayed "the promise of a free, equal and prosperous nation" by eroding the universality of freedoms (Balton, 2025), thereby betraying the foundations, substance and functions of democracy (Isike & Onapajo, 2017; SAT-International, 2025). Painfully, SAT-International (2025: n.p.) concludes that the ANC betrayed "the 1994 compromise by entrenching corruption, weakening democracy and failing South Africans," as well as undermining the rule of law and judicial independence, and weaponising state institutions, leaving "citizens at the mercy of criminals."

Manifestly, the GNU elitism complicitly perverts the universality of freedoms and rights. Consequently, the erosion of freedoms in South Africa "has become worse in recent times" (Balton, 2025) owing to intensified political deception, including through state and democratic institutions. The GNU itself was decided exclusively by elites in secrecy, without consulting constituencies (Tony, 2025). Zille, knowing the origins of the GNU conception, took along Ramaphosa's rudderless ANC elitists (Seepe, 2024a, 2025d). However, Tony (2025) reveals Zille's fixation with her "hobby horses" that lack considerations for South Africa's future trajectory. Rather than enhancing the DA brand of GNU, Zille remains fixated on her 2019 forecast of collapsing the ANC. The ANC is not indispensable for South Africa; however, disguising strategies for collapsing the ANC as GNU national unity amounts to mendacious political deception. Consistent with Zille's 2019 forecast, Seepe (2025d: n.p.) notes that Ramaphosa's "smoke and mirrors leadership is leading the ANC into oblivion." Unsurprisingly, Ramaphosa's ANC has crossed the DA's multiple GNU membership red lines, yet the DA remains entangled in Ramaphosa's presidential incumbency self-preservation as a catalyst to ANC collapse, at the expense of accountability, rule of law and the universality of freedoms. However, the ANC/DA GNU coalition emboldens governance recalcitrancies among Ramaphosa's ANC factional elites in intra-party rivalries and succession battles, while Ramaphosa continues to avoid accountability, pervert the rule of law and subvert the universality of freedoms.

According to Seepe (2025d: n.p.), “Ramaphosa’s last gasp of power is the GNU;” and when he steps down, “there will be nothing left of the ANC.” Despite Ramaphosa repurposing himself as guardian angel for South Africa, state capture persists (Sebola & Tsheola, 2024). Evidently, Ramaphosa constituted the GNU in service of his presidential incumbency self-preservation and perversion of accountability. During the 6th Parliament, the DA sought to hold Ramaphosa accountable for the Phala Phala scandal. Being the second largest GNU party with 6 Cabinet seats, the DA now characterises Phala Phala scandal, in Zille’s words, as “irrelevant.” That the Phala Phala saga involves unlawful conduct is conclusively attested to by Mohammed Ameen’s April 2025 conviction involving October 11, 2017 arrest for possession of undeclared \$544 200 (Daniels, 2025). Court convicted Ameen on charges of money laundering and contravention of Exchange Control Regulations (Daniels, 2025) similar to those that the NPA refuses to pursue against Ramaphosa over Phala Phala saga (Seepe, 2025b), amidst retired Chief Justice Section 89 Panel concluding that Ramaphosa had a case to answer. Responding to Ameen’s conviction, ATM leader, Vuyo Zungula (cited in Daniels, 2025: n.p.), painfully observes: “... other people are arrested ... held accountable for having undeclared foreign currency in their possession but in this case, because it involves the president, there are double standards the rich, the powerful, politically-connected individuals will always be exempt from being held accountable.” Complicity in exempting Ramaphosa from accountability and obedience of the nation-state’s law, for which Ameen was convicted, undermines the universality of freedoms.

With DA’s GNU complicity, fusion of Ramaphosa’s impunity with state territory as personal presidential fiefdoms is sustained. The EFF’s and MK Party’s condition for GNU membership is the removal of Ramaphosa from presidency, whereas the DA would not accept presidencies of Gwede Mantashe (ANC chairperson) nor Paul Mashatile (ANC and state deputy president) (Tony, 2025). The DA suggests that it voted Ramaphosa into the presidency on June 14, 2024 and joined the GNU to, in Steenhuisen’s (2025: n.p.) words, “keep the destructive forces of MKP and EFF out, and contribute to building South Africa.” No single South African voter had through their May 2024 vote determined that national unity and stability entailed “keeping-out” MK Party and EFF. Ramaphosa’s suggestion that voters had determined that leaders should set aside their political differences is incongruent with the act of “keeping-out” other parties and reckless divisiveness. Instead, GNU proponents have irresponsibly embraced spurious scaremongering. The DA’s complicity in protecting Ramaphosa’s presidency and shielding him from accountability means that the DA has lost its claim to moral leadership about the rule of law and accountability. Therefore, this GNU does not restore South Africa’s “state idea” of dignity, equality before the law, unity and universality of freedoms. Disambiguation of its foundations shows that this GNU is deceptive, hoping to reincarnate the ANC’s majoritarianism through the DA’s agency in GNU politics, effectively repurposing GNU government as an omnipotent law breaker that breeds contempt for law. Unlike Mohammed Ameen, Ramaphosa is immunised from prosecution for undeclared possession of \$580 000 around February 2020. This article concludes, therefore, that this GNU elitist democracy serves politicians, protection of presidential incumbency and corrupt patronage politics, rather than national unity and stability.

4. Conclusion and Recommendations

Theoretically, this article has argued that freedoms are indivisible and that the “state idea” is imperative to their universality because they are not “a natural right.” To hold, universality of freedoms require democratic “state idea” consciencism about unity, inclusivity, accountability and obedience of the nation-state’s laws by all citizens and commanders as equals. Manifestly, the article showed that the ANC has historically abused democratic majoritarian politics to institute elite democracy and undermine the universality of freedoms by shirking the rule of law and accountability. Disconcertingly, the DA’s post-2024 elections recasting of the Phala Phala saga as “irrelevant” is tantamount to repurposing the GNU government as a law-breaker that teaches society by example that freedoms are divisible, rather than universal, thereby sustaining disharmony among abstract liberalism, social status as basis for rights and ordinary South Africans’ lived experiences. Effectively, the DA’s GNU membership reinstitutes elitist democracy and tacitly hands-back state territory and power to Ramaphosa’s ANC as personal fiefdoms for regeneration of political power, exemption from obedience of the nation-state’s laws and presidential

incumbency self-preservation. Therefore, the article concludes that the GNU subverts democracy in service of politicians and continuities of Ramaphosa's and ANC's governance recalcitrancies, rather than fostering the universality of freedoms and national unity. The article recommends that national unity and stability require consciencism "state idea" founded on obedience of the nation-state's laws by citizens and commanders alike, as the basis for the universality of freedoms.

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Johannes TSHEOLA (PhD), Professor

ORCID ID: <https://orcid.org/0009-0001-6548-4291>

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