Scientific Research Publishing

Journal of Geographic Information System, 2026, 18(5), 275-288
https://www.scirp.org/journal/jgis
ISSN Online: 2151-1969
ISSN Print: 2151-1950

Towards a Framework for National Spatial Data Infrastructure Development in Kenya: A Comparative Analysis of Established SDIs

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How to cite this paper: Mwange, C. (2026) Towards a Framework for National Spatial Data Infrastructure Development in Kenya: A Comparative Analysis of Established SDIs. *Journal of Geographic Information System*, **18**, 275-288.
https://doi.org/10.4236/jgis.2026.185015

Received: August 31, 2026
Accepted: September 25, 2026
Published: September 28, 2026

Abstract

Spatial Data Infrastructures (SDIs) offer immense potential, including sustainable land governance, socio-economic growth, innovation, and environmental management. Despite these benefits, SDI development in Kenya remains constrained by institutional and legal gaps, and implementation bottlenecks. Grounded in a comparative document analysis of primary legal, policy, and strategy frameworks, this paper evaluates five mature national SDIs (USA, Canada, Australia, Poland, and South Africa) across explicit operational maturity criteria. By synthesizing cross-case evidence and international best practices against Kenya's local legal and institutional context, this study proposes a strategic, three-phase framework tailored for Kenya: SDI Inception, SDI Planning, and SDI Implementation. The proposed framework provides decision criteria for adopting a hybrid governance model, emphasizing clear national objectives, adaptive governance, robust legal directives, and cross-sector partnerships. Serving as a conceptual decision-support tool, the framework offers actionable guidance for policymakers and geospatial custodians to operationalize sustainable SDI development in Kenya and similar developing countries.

Keywords

Spatial Data Infrastructure, SDI, Framework, Kenya

1. Introduction

1.1. Background

Spatial Data Infrastructures (SDIs) are intended to foster collaboration among diverse stakeholders, including spatial data producers, business establishments, academic researchers, and the general populace [1]. An SDI encompasses the technical, institutional, and governance frameworks required to support seamless access to geographic data and services across local, national, regional and international jurisdictions [2]. Each jurisdiction successfully implementing SDI accrues many benefits, including cost effective access to quality data, business opportunities, improved innovation, sustainable land management, among other benefits.

SDI is the evolution of autonomous spatial information systems, such as corporate Geographic Information Systems (GIS), into a network of heterogenous frameworks of spatial data and services [3]. Rajabifard *et al.* [4] argued that SDIs constitute stakeholder networks, permitting organizations, academic researchers, and the general populace to seamlessly share data and services.

Despite emerging as a relatively recent paradigm in the 1990s, SDIs have achieved global recognition. The urgent need for SDIs is underscored by the fact that the vast majority of information utilized in land management and urban planning inherently possesses a spatial dimension [5].

To date, prominent SDIs comprise nationwide undertakings, such as the South African Spatial Data Infrastructure (SASDI); supranational SDIs such as the Infrastructure for Spatial Information in the European Community (INSPIRE); and the Global Spatial Data Infrastructure (GSDI). An SDI encompasses a multi-layered framework that hosts spatial datasets and services conforming to agreed standards, supported by policies and institutional arrangements [6].

A typical SDI comprises components such as catalogues and geoportals facilitating the discovery and use of spatial datasets and services, and metadata that describe the structure, characteristics, and form of the datasets and services. More fundamentally, an SDI hosts commonly used and standard-compliant spatial datasets, which promote interoperability, sharing and reuse of data. It also encompasses an institutional framework made up of various organizations and stakeholders responsible for facilitating the efficient and effective production and management of spatial data. Finally, SDIs are underpinned by governance and operational policies that actively regulate and facilitate data sharing, open data frameworks, privacy protection, cost-recovery models, and data custodianship mandates [1] [4].

Some researchers conceptualize SDI as a broader information infrastructure, with inherent complexities in both establishment and maintenance. Budhathoki and Nedović-Budić [7] observed that the SDI body of knowledge lacks robust theoretical grounding and operational depth required for long-term viability. Consequently, numerous initiatives experience challenges, whereas established SDIs struggle with operational bottlenecks and limited adaptability to diverse user requirements.

1.2. Research Problem and Objectives

Given the complexity of SDIs and its reported slow development across the world (see [8]-[10]), the need arises to review workable development frameworks of SDI within its social, economic, cultural and political context. Establishing this framework is necessary to articulate the intersection of SDI development workflows, coordinate inter-institutional system deployment, and enable long-term platform scalability to support a growing user base.

While SDIs give rise to significant societal benefits, ranging from economic and sustainable development to enhanced land administration; SDI implementation across the African continent continues to face challenges and limited progress [8]-[10]. Multiple factors contribute to the reported slow progress. Primarily, the core principles of SDI remain widely misinterpreted. Additionally, given the intricate nature of SDI systems, standard implementation models frequently fail to align with local socio-technical contexts. Third, the organizational and institutional frameworks in the setting may be the impediment to SDI development.

The overall objective of this study is to conduct a comparative qualitative document analysis of primary legal, policy, and institutional frameworks from mature national SDIs to derive a decision-support implementation framework tailored to Kenya's context.

2. Theoretical Background

Successfully building an SDI requires a thorough understanding of the core SDI principles, constituent components, and the specific roles each of them plays in the broader SDI architecture. This section presents an overview of core SDI concepts and development models.

2.1. SDI Components

According to Budhathoki and Nedović-Budić [7], three themes support SDIs: policy and organization (politics, institutions, culture and management); interoperability and sharing (standards, policies and custodianship); and finding and use of the datasets in the SDI (technical and technology). A characteristic SDI consists of organizations collaborating with each other, each of which expose spatial data under their custody via geospatial services to serve a broad range of user needs.

Typically, geospatial data within an SDI are organized into three primary layers, namely foundation data (e.g., geodetic controls, orthophotos and topographic maps), framework data (e.g., land use, transportation, soil and hydrography), and application data (e.g. protected areas, healthcare facilities, transportation networks, land use zones, and flood hazard boundaries). Government-backed and funded foundation and core framework layers constitute the essential geographic foundation. These primary datasets are managed by designated public authorities generally known as custodians, and should be distributed to end users at minimal cost [11] [12].

Metadata broadly refer to the structured information that describes existing datasets and spatial services in terms of cost, source, form, ownership, content, age, condition, quality, format, and fitness for purpose. Metadata enables a better understanding of data and services, and facilitates widespread data and service sharing. Furthermore, these platforms enable users to discover relevant datasets and services, assess their quality and applicability, and seamlessly retrieve or consume the underlying spatial assets.

While the breadth and detail of metadata can vary, it should align with recognized international frameworks, such as the *ISO* 19115: *Geographic Information - Metadata* standard. Using metadata, the SDI community is able to organize (inventory), catalogue (index to permit structured searches), and document (provide adequate information) spatial datasets or services [13].

Institutional arrangements facilitate engagement and cooperation among key actors in the SDI. They play a cardinal role in establishing and preserving cross-sector collaboration throughout the SDI lifecycle [3], and are typically based on legislation, regulations, policies, agreements or negotiation. As expected, institutional arrangements post more challenges than the other SDI components [14], even though they play a fundamental role by facilitating access to data in the guardianship of custodians. Such collaborative mechanisms serve to optimize dataset and metadata upkeep, minimize redundant data collection, drive the development of datasets, and guarantee conformity with national and international standards.

Standards allow organizations to seamlessly share data, enrich the data and service quality, and facilitate data interoperability [13]. The latter is the ability of datasets from diverse entities to communicate despite their differences, operating across syntactic interoperability (to manage data formats and exchange), schematic interoperability (to define classifications and hierarchies), and semantics (to harmonize the meanings of terms) [15].

SDI are supported by a range of standards, such as data-, information technology-, educational-, performance- and organizational-standards. Data standards ensure structural quality and smooth cross-system data exchange, information technology (IT) standards govern hardware, software, and networking protocols, educational standards outline required competencies for geospatial practitioners, organizational standards define administrative procedures, and performance standards are used to evaluate SDI efficacy.

Traditionally, the supporting technologies for SDI encompassed geoportals, clearinghouses, internet, and standardized web services [16]. Recently, the evolution of SDIs has been driven by the integration of modern digital paradigms, including Cloud Computing, Volunteered Geographic Information (VGI), Linked Open Data, and Big Data analytics. More crucially, the emergence of Artificial Intelligence (AI) and Machine Learning (ML) and geospatial artificial intelligence (Geo-AI) along with the Internet of Things (IoT) and 3D spatial twin environments, is transforming SDIs from static data repositories into dynamic, automated, and predictive analytical platforms [17].

Policies serve as the strategic and operational frameworks required to accelerate SDI development, defining how the infrastructure is established, governed and sustained. High-level strategic policies establish overarching directives that enforce compliance with mandatory standards, governance protocols, and operational workflows. On the other hand, operational policies address lower-level concerns such as spatial data lifecycle, guidelines and manuals for data collection [3].

SDI Policies are primarily needed to support data development (the need for standards and metadata), data access, innovation and commercialization and intellectual property (protecting innovation by copyright, trademarks, patents and licenses), data custodianship, data security, funding, technology and training and capacity building.

Finally, SDI human component encompasses both the operational personnel who manage the system and the end users who interact with it, including those who transform baseline data into value-added products. This stakeholder network includes geospatial specialists, ICT professionals, administrative managers, spatial data vendors, and geo-literate citizens.

2.2. SDI Development Models

There are several SDI development models, notably the top-down and bottom-up models, and the product and process models. This section expounds these models, and discusses their relevance in different institutional and governance contexts.

The top-down model is generally backed by directives such as an executive order, regulation or legislation, and can therefore be considered to emanate from the vision of the executive. Under this framework, spatial data providers publish their datasets to ensure they are discoverable and accessible within the SDI ecosystem [3]. Prominent implementations of this top-down model include the United States National Spatial Data Infrastructure (NSDI) and the SASDI of South Africa.

According to Tumba and Ahmad [18], the unpopularity of top-down strategy stems from the slow implementation rates across various contexts. In addition, effective SDI governance necessitates the need for participatory input from grassroots stakeholders, an aspect where centralized, top-down frameworks often fall short.

Conversely, the bottom-up or voluntary strategy serves as an alternative to the top-down model. Under this paradigm, the SDI evolves organically from decentralized, grassroots initiatives led by early adopters. Although less frequently deployed, this user-driven approach was instrumental in building some mature SDIs, such as the Canadian Geospatial Data Infrastructure (CGDI) [3].

According to Rajabifard *et al.* [4], the objective of the product model is to link existing and potential datasets within the control of the SDI. Also referred to as first generation SDIs, the product model was predominant in the earlier SDIs. The model focused on data development and management, with technology being the main source of complexity [19]. Overall leadership responsibility in these SDIs was often bestowed on National Mapping Organizations (NMOs), such as Survey of Kenya.

In contrast, process-based models center on management frameworks designed to govern spatial information assets [4]. Frequently designated as second-generation SDIs, this strategy demonstrates higher responsiveness to varied user requirements through structured processes that encourage inter-agency collaboration. Furthermore, oversight in these systems is often delegated to independent, purpose-built organizational structures.

The context supporting SDI development can be regarded as a social system, that is, a network of interconnected entities, such as tribes, communities, counties, and organizations, collaborating to address common goals. The underlying dynamics of this social system, including prevailing cultural norms, significantly shape the strategies adopted for SDI development [4] [7].

A product-based strategy is best suited when the primary objective is to integrate spatial datasets across distinct political and administrative tiers. Conversely, if the overarching goal is to establish a governance structure that optimizes spatial information asset management, a process-based model becomes the more effective strategy.

Likewise, political governance dictates the optimal framework. Decentralized federations (such as counties in Kenya under the new constitutional dispensation) favor process-based models to accommodate voluntary inter-institutional engagement. On the other hand, non-federated systems can strategically deploy either of the models to achieve maximum benefit [4].

Lance *et al.* [20] raised concerns that conventional public sector administrative frameworks remain largely incompatible with the institutional structures required for successful SDI deployment. This stems from the fundamental nature of SDIs as cross-boundary initiatives, whereas public administration operates within rigid silos delineated by departmental divisions, organizational hierarchies, official mandates, and sector-specific programs.

3. Methodology

The study adopts a qualitative, comparative document analysis designed to examine mature national SDIs (NSDIs) and derive an operational development framework tailored for Kenya and similar developing countries, which has been reported to be slow [10]. For this study, a mature NSDI was defined as one demonstrating the characteristics shown in **Table 1**, derived from sources such as [21].

Primary sources of data for the study include legislative and policy frameworks, such as national acts (e.g., South Africa's Spatial Data Infrastructure Act 54 of 2003 [22]), executive mandates (e.g., US Executive Order 12906 [23]) and peer-reviewed journal and conference publications (such as Bossler *et al.* [1], Kordgheshlaghi *et al.* [21] and Rahman and Szabó [24]). It also includes official best-practice compendiums (e.g., European SDI Best Practice guidelines [25] and GeoConnections [3]), policies (such as South Africa's pricing policy [26]) and multi-view status evaluations, such as INSPIRE state of play [27].

3.1. Document Selection and Case Sampling

A purposive sampling strategy was employed to select five mature national SDIs

(USA, Canada, Australia, Poland, and South Africa) representing distinct geographical regions, legal traditions, and SDI governance structures (top-down, bottom-up, and hybrid models).

The USA, Canada, Australia, Poland, and South Africa were chosen for geographical diversity representing North America, Europe, Oceania, and Africa, which represents a good mix of top-down and bottom-up models.

Table 1. Characteristics of a mature NSDI.

Criterion	Operational definition	Evidence
National scope	The SDI operates at the national level	National mandate or directive
Operational status	SDI has moved beyond the conceptual stage	Review of SDI status from various sources in the country
Data access	Multiple spatial datasets/services are discoverable and accessed	A publicly available geoportal/catalogue
Institutionalization	Formal or established institutional arrangements exist	Legislation, policies, agency or governance body
Stakeholder participation	Multiple public/private/academic actors participate	Governance documentation, and Legislation, policies, agency or governance body
Sustained development	Evidence of continuing operation/development	Status reviews, plans, programmes, funding or evaluations

Source: own study.

The study population encompasses countries maintaining mature SDIs characterized by a well-established operational base and an active geoportal delivering diverse spatial datasets and services, as shown Table 1. A sample was selected from this target group, as indicated in Table 2.

Table 2. Data sources.

Continent	Target group	Sample
Americas	USA, Canada, Brazil, Argentina, Chile, Mexico, Uruguay, and Venezuela	USA, Canada
Africa and Middle East	South Africa, Abu Dhabi, and Saudi Arabia	South Africa
Asia and Oceania	Australia, New Zealand, and India	Australia
Europe	The Netherlands, United Kingdom, Germany, Poland, Spain, France, Norway, and Portugal	Poland

Source: own study.

3.2. Synthesis and Framework Development

Table 3 presents a comparative overview of the reviewed cases, highlighting four main criteria: objective of the SDI, directives in place to drive SDI development, collaborative partnerships, and institutional frameworks.

Table 3. Comparative overview of the selected cases.

Country	SDI Name	SDI Objective	Directives	Collaborative Partnerships	Institutional Framework
South Africa	South African Spatial Data Infrastructure (SASDI)	Facilitate spatial data sharing and avoid data duplication.	The SDI Act of 2003	Committee for Spatial Information (CSI) and National Spatial Information Framework (NSIF)	Lead agency: DRDLR, Implementation committee: the CSI, which appoints data custodians and the NSIF, which coordinates SDI development.
Poland	Krajowa Infrastruktura Informacji Przestrzennej (KIIP)	Promote entrepreneurship and job creation.	The Act of 2009 and the INSPIRE directive of 2007	Governmental relations and administrative procedures	Lead Agency: Minister of Administration and Digitization/General Surveyor of Poland Implementation Committee: National Committee
Australia	Australian Spatial Data Infrastructure (ASDI)	Drive sustainable development while addressing global and environmental challenges.	None	ANZLIC, in association with government, private, public, and academic sectors	Lead Agency: ANZLIC; Implementation committee: one representative from each from the eight state and territory governments.
Canada	Canadian Geospatial Data Infrastructure (CGDI)	Foster economic growth and employment through innovation in information-based industries.	None	All-inclusive partnerships through GeoConnections	Lead Agency: GeoConnections Implementation Committee: Management Board consisting of officials from the federal agencies, and representatives from academia and industry.
USA	USA National Spatial Data Infrastructure (NSDI)	Improve efficiency and accessibility by standardizing high-quality geographic data, lowering costs, and maximizing data utility.	Executive Order number 12906 of 1994	Expanded from federal agencies to a broad-based cross-sector approach	Lead Agency: FGDC. Implementation committee: chairpersons of the thematic subcommittees and "cross-cut" working groups, and representatives from federal agencies and other groups.

Source: own study.

Poland initiated its national SDI (KIIP) with the primary mandate of fostering entrepreneurship and employment growth. This case demonstrates that SDIs have a chance of success when anchored to high-level strategic goals, particularly national-level socioeconomic objectives. Furthermore, KIIP highlights the essential role of state intervention in driving SDI development. Concurrently, the European

Community's INSPIRE Directive mandates that member states establish supportive legislative frameworks, fund capacity building for professionals and citizens, and actively raise public awareness of national infrastructures like KIIP.

In Canada, GeoConnections has adopted an inclusive governance model by forming multi-stakeholder partnerships across government, industry, and academia. The national SDI, CGDI, operates primarily through a bottom-up model, prioritizing broad stakeholder mobilization. Consequently, CGDI functions as a sector- and industry-wide initiative that emphasizes collaborative decision-making to resolve emerging operational and technical challenges.

South Africa has adopted a top-down governance model, establishing the SASDI through formal legislative and policy frameworks. This structured approach explicitly delineates the roles and responsibilities of key stakeholders, including data custodians. Consequently, SASDI's well-defined regulatory guidelines have enhanced institutional clarity and stakeholder comprehension of the SDI.

The United States national SDI (NSDI) demonstrates that executive-level political backing exerts a positive influence on SDI development. Although implemented within a fragmented ecosystem characterized by competing stakeholder interests, strategic policy frameworks were successfully established to govern this complex environment. Furthermore, the US experience highlights that sustained research initiatives and dedicated financial resources are critical determinants of long-term SDI viability.

The Australian national SDI (ASDI) is strategically designed to optimize economic, social, and environmental outcomes across the nation. Its core agenda focuses on industrial growth, advancing the digital information society, and addressing contemporary global challenges, including environmental degradation and resource depletion. Notably, a defining hallmark of the ASDI is its heavy reliance on structured communication and stakeholder consultation strategies.

4. Results and Conclusions

Based on the reviewed cases, the proposed SDI development framework is presented in **Figure 1**. The extracted qualitative data were categorized using thematic analysis centred on objective of the SDI, directives in place to drive SDI development, collaborative partnerships, and institutional frameworks. Cross-case synthesis was then performed to extract best practices and bridge international experiences with Kenya's context, resulting in the proposed three-phase development framework cantered on SDI inception, planning and implementation.

A clear impetus for SDI development is the creation of awareness by formulating clear SDI objectives (see **Table 3**). For instance, Poland prioritized economic expansion by driving SDI implementation through targets focused on entrepreneurship and job creation. Similarly, Canada leveraged its SDI framework to enhance regional and global competitiveness, foster innovation, elevate national productivity, and catalyse emerging spatial information markets. Borrowing from this leaf, Kenya can formulate SDI objectives suitable to the Kenyan context, such as better land information management, development control, and job creation and innovation.

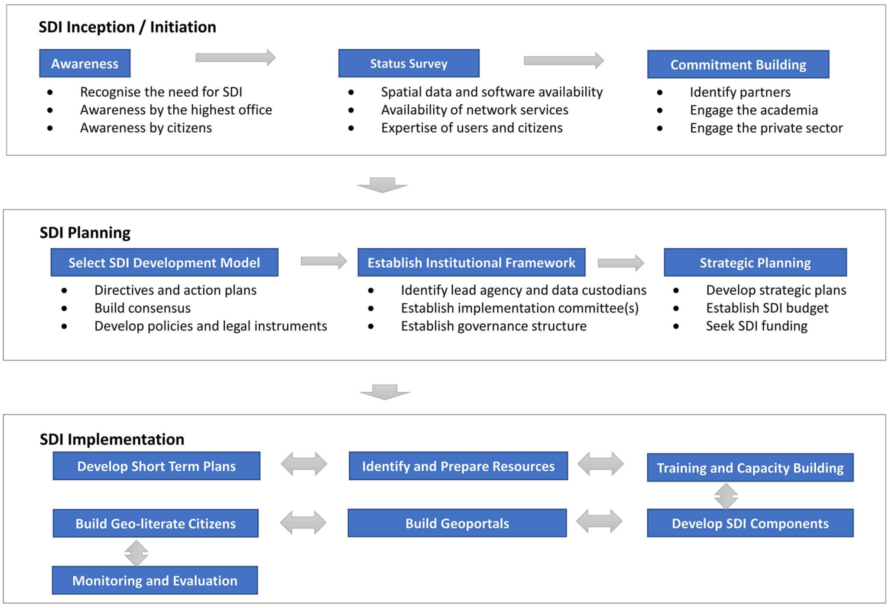

Figure 1. The proposed SDI development framework.

Countries with mature SDIs conduct regular reviews to ascertain the status of the SDI. Such reviews can be done regularly at any stage of the SDI development. Notable examples of countries conducting regular reviews include Poland through Inspire State of Play, and the USA through regular initiatives such as scorecard analysis.

Kenya follows a decentralized governance model, and may utilize either the top-down or bottom-up model for SDI development. If the top-down approach is preferred, then directives in the form of strategic policies and legal instruments should be developed leading the establishment of the SDI, and setting up relevant institutional frameworks. The directive can identify data custodians, their roles and responsibilities, and implementation committee(s). Conversely, where a bottom-up model proves more suitable, establishing robust collaborative partnerships across all governance tiers becomes essential, like the case of Canada. This paradigm requires targeted policy mechanisms that address operational constraints specific to individual agencies, data themes, and emerging technologies. Key policy priorities within this scope encompass data pricing, access protocols, licensing frameworks, sharing mechanisms, and intellectual property (IP) rights.

As shown in Table 3, a cardinal component of SDI development is commitment building. This involves building consensus, establishment of directives and collaborative partnerships. Such partnerships may involve identifying and creating the mandate of custodians, identifying resources needed to develop the SDI, and establishing the roles and responsibilities of the stakeholders. The reviewed evidence demonstrates that mature SDI routinely incorporate private enterprise to expand spatial data availability, engineer information systems, and operationalize national geoportals.

The lead agency model has been a common practice in SDI development. Often, the lead agency is associated with the national mapping organization (NMO) such as Survey of Kenya, or in some cases the National Statistics Agency (NSA) such as the Kenya National Bureau of Statistics. However, the reviewed cases show that careful selection of the lead agency should be considered. Depending on the methodology preferred, an inter-agency committee(s) spearheading SDI may be preferred, since no single organization can develop a national SDI. The role of such a committee is to foster a conducive environment and facilitate collaboration for successful SDI development.

Mature SDIs essentially depend on sustainable financing frameworks. Developing multi-year strategic plans to delineate core SDI operations provides the baseline for reliable budgetary forecasting - a methodology demonstrated across all evaluated case studies, typically through rolling five-year planning cycles. For Kenya, establishing sustained state funding is critical; while donor assistance offers valuable supplementary support, it must not serve as the primary financing mechanism. Although initial SDI establishment may rely heavily on public treasury allocation, long-term viability necessitates the adoption of self-financing mechanisms or cost-recovery strategies.

SDI implementation requires the identification, mobilization, and preparation of core operational resources, including human capital, financial investments, and software infrastructure. Beyond resource allocation, the execution phase may encompass short-term strategic planning, workforce skill alignment, capacity building, and the cultivation of geospatial literacy among the broader citizenry. Crucially, technical deployment involves data standardization, metadata catalogue development, and geoportal establishment. To ensure long-term viability, continuous governance and assessment measures, such as annual performance reviews, must be embedded into the framework to systematically evaluate progress across SDI components and verify alignment with overarching objectives.

5. Conclusion

In summary, this study establishes a framework for advancing Kenya's SDI by conducting a comparative document analysis of primary legal, policy, and strategy frameworks from mature NSDIs. By synthesizing evidence and actionable inferences from established international cases against Kenya's context, the paper outlines a structured decision-support sequence designed to guide governance, legal grounding, resource allocation, and technical implementation. This sequence encompasses three core operational phases: SDI Inception, SDI Planning, and SDI Implementation.

Acknowledgements

The author is grateful to the Advancing Collaborative Research in Responsible and Smart Land Management in and for Africa (ADLAND), financed by the German organization Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), who organized a research-writing workshop in Dar-es-Salaam, Tanzania, at which the theoretical framework of this paper was developed.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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