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Development of A Framework Using Findable, Accessible, Interoperable, and Reusable Model for Data Management Practices in Nigerian Universities

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Abstract- ***The era of digitalization has made data-driven discovery a new paradigm, creating an urgent need for proper data management. While Nigerian universities generate vast amounts of data through diverse academic and research activities, they suffer from fragmented and inefficient data practices that hinder data reusability, interoperability, and collaboration. Recognizing the critical gap of lacking a standardized, empirically tested framework tailored to the Nigerian context, this study developed and validated a FAIR-compliant framework based on the Findable, Accessible, Interoperable, and Reusable (FAIR) principles. This was achieved by designing a formal, scalable blueprint using the semantically rich OntoUML modeling, which integrates a centralized repository, metadata management, an interoperability layer, and a formal governance structure. The framework's adherence was confirmed via a two-stage validation: first, through objective FAIR-Checking adherence testing, which yielded a perfect score across all core FAIR metrics (F1, F2, F4, A1, I1, I2, R1.1, R1.2), and second, through expert reviews, which validated its practical usability and compliance with local regulations like the Nigerian Data Protection Regulation (NDPR). Consequently, the research bridges the gap between theory and application, providing a viable, actionable solution that makes significant contributions to improved data governance, enhanced research collaboration, and the development of trustworthy, efficient data systems in Nigeria and beyond.***

Index Terms- ***FAIR, Data, Management, Findability, Accessibility, Interoperability, Reusability, Principles, Framework, Model, Nigerian, Universities.***

I. INTRODUCTION

The rise of digitalization has transformed the contemporary research process into a data-driven discovery paradigm, urgently necessitating proper data management to ensure data are reusable, reproducible, and accessible. Nigerian universities generate massive amounts of diverse data, from student records to research outputs, yet their existing data management practices are often fragmented, inefficient, and characterized by system incompatibility [1], which ultimately leads to data loss, duplication of effort, and limited research impact [2], [3], [4], [5]. Effective data management, encompassing creation, processing, storage, and sharing [6], is crucial for enhancing data quality and reuse [4]. To address these issues, the internationally recognized FAIR Data Principles offer a promising framework for promoting data sharing, reuse, and reproducibility, making its development essential for Nigerian higher education [4].

The research problem stems from the wide variance in data management practices across Nigerian universities, which typically rely on a mix of ad-hoc systems, partially implemented lifecycle models, and institution-specific protocols, resulting in systems that are often inefficient, lack interoperability, and do not make data reusable [7], [8], [9]. Crucially, a lack of consistent privacy and security standards means few institutions meet global benchmarks [9], [10], [11], [12]. While some localized efforts exist, such as the development of an ontology for a single institution [13], they underscore the need for a generalizable, empirically validated framework rooted in international standards.

Therefore, a significant dearth of research exists on a robust, scalable, and tested FAIR data framework for Nigerian universities to streamline practices, enhance data reusability and interoperability, and enforce consistent privacy and security standards [9]. The study was thus aimed at developing a framework using the FAIR model for data management practices in Nigerian universities, with specific objectives to design, develop, test, and validate the framework against specific FAIR metrics (F1, F2, F4, A1, I1, I2,

R1.1, R1.2) using the FAIR Checking Summary Sheet and expert reviews.

This study is justified by the urgent need to harness data's potential in Nigerian universities through the implementation of the FAIR Data Model. The framework is anticipated to improve data transparency to foster public trust; enhance data impact by enabling collaborative research and secondary analysis; accelerate scientific discovery by making data widely available; and increase international collaborations by aligning local data with global standards.

II. RELATED WORKS

The development of a framework using FAIR data principles for data management practices in Nigerian universities requires a deep understanding of research that has been carried out in similar contexts. Review of these works, their methodologies, findings, and limitations provides a basis for this study and how data management practices can be structured and improved to align with FAIR principles, which are critical in ensuring the effective use and sharing of data within academic and research environments.

The research is framed by the Knowledge Infrastructure Framework (KIF) [10], which conceptualizes data as an integral part of a broader infrastructure encompassing the networks, standards, and tools that support knowledge creation. This view emphasizes that data must be understood within an interconnected system that fosters research and innovation. The KIF provides a systematic approach to managing an organization's knowledge assets [14], and its flexibility makes it a valuable tool for optimizing knowledge management in diverse settings, leading to improved collaboration and innovation [15], [16].

Global reviews of FAIR principles highlight their role in promoting machine-actionable data reuse, which is essential for research efficiency [17]. Successful adoption relies on community-driven standardization and the necessity of a high-level framework to prevent the development of incompatible solutions [18]. However, a significant limitation of these global studies is their lack of specific focus on Nigeria or the unique operational challenges faced by university systems in sub-Saharan Africa [17], [18].

In the Nigerian context, research has focused on solutions for collaboration and data sharing. Akinnuwesi and others investigated the Knowledge Grid (KG) as an intelligent system to address challenges in data resource sharing [19]. Their systematic review identified a lack of virtual collaboration platforms and independent governance structures that complicate inter-institutional work. They proposed a KG model tailored for Nigerian university systems to pool data resources, but also noted significant technical constraints and economic barriers, including limited infrastructure and stakeholder resistance to change [19].

A study of Nigerian policy documents found that while FAIR principles are not explicitly named, they contain a significant amount of "FAIR Equivalent" terminology, indicating a crucial "policy window" for formal adoption in sectors like digital health, which can be extended to academia [20]. Furthermore, efforts in professional development include the outline for a curriculum designed to train data stewards in applying FAIR principles, though this work focuses on education rather than model development [21].

Research into implementation methodologies by Inau and others guides the implementation of FAIR principles [22]. The research outlined a protocol for a scoping review of FAIR data principles and practices, highlighting the need to analyze adoption and implementation in data stewardship, with future challenges anticipated in the harmonization of disparate datasets. Additionally, the development of a conceptual model using an ontology is proposed to clarify the complex semantics of FAIR principles, offering a structured blueprint for designing systems that are "FAIR by design" [23].

A practical contribution [13] that developed an adaptable ontology for a single Nigerian university, demonstrating how to build a semantically structured data model from relational databases and testing it with SPARQL queries. However, their work's primary limitation is its localized scope and lack of explicit validation against international FAIR standards. In separate research that addressed the challenge of restricted data, researchers found that methods related to access control and usage licenses are key to making sensitive data FAIR-compliant [24].

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Other reviews of Quality Management Systems (QMS) in higher education found that QMS models, like ISO 9001, dominate but often do not specifically address data management practices [25]. While some discussions emphasize the role of FAIR in enhancing data governance and transparency in Nigeria [26], they often focus on general challenges and lack empirical data or actionable strategies specific to university systems. This body of work highlights a critical need for a comprehensive, empirically validated, ontology-based framework that integrates technological, policy, and cultural considerations to address the unique challenges of data heterogeneity and management in Nigerian universities.

III. METHODOLOGY

This study adopts a developmental research design that is focused on creating a robust framework that implements the FAIR (Findable, Accessible, Interoperable, and Reusable) principles for data management in Nigerian universities.

3.1. System Design

The framework is a standardized, modular system designed around the four core FAIR principles to address inadequate data management in Nigerian universities. The architecture, illustrated in Fig. 3.1, integrates a centralized repository, standardized metadata schemas, and a secure access control system for a scalable solution. The Data Repository and Data Acquisition Module form the foundation, providing centralized storage for all institutional data (including administrative data, research data, and student records) from diverse sources, which eliminates data silos. During ingestion, data undergoes preprocessing, including validation and anonymization for privacy compliance, notably with the Nigerian Data Protection Regulation (NDPR). This module directly supports the FAIR principles by ensuring data integrity, providing indexing for findability, and implementing role-based access for security.

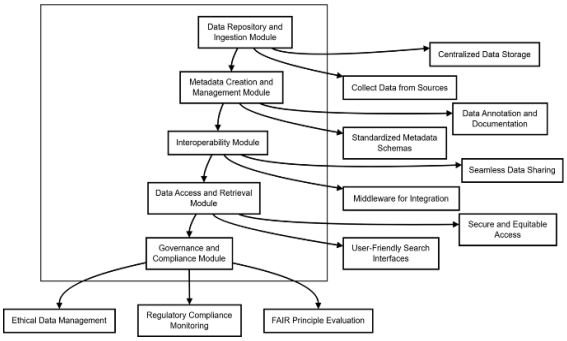

Fig. 3.1. Designed Framework Architecture

The Metadata Creation and Management Module annotates all institutional data using standardized schemas like schema.org, and includes semantic technologies such as ontologies and controlled vocabularies to enhance discoverability and interoperability. The Data Access Control and Retrieval Mechanisms ensure secure and equitable access, balancing data availability with confidentiality. Access control enforces authentication and authorization protocols (enhanced by encryption and multi-factor authentication) in compliance with the NDPR, while intuitive retrieval mechanisms use advanced search tools and metadata indexing to allow authorized users to efficiently find and use relevant data.

The Interoperability Layer acts as a critical middleware component, facilitating seamless data sharing and integration between systems both within and outside the university. It uses standardized protocols, APIs, and semantic ontologies (e.g., OntoUML) to harmonize data from various sources, ensuring that data semantics are preserved during exchange to support interoperability and reusability. Finally, the Governance Framework (Compliance and Monitoring Module) is the overarching component, defining policies and user roles to ensure data is managed ethically and securely in compliance with institutional and regulatory requirements. This module also utilizes metrics to monitor the system's adherence to all FAIR principles, ensuring the long-term sustainability and effectiveness of the data management system.

3.2. Use Case Diagram

The use case diagrams, shown in Fig. 3.2, illustrates the interactions between different user roles and the components of the FAIR data management system. The primary actors include the administrators, faculty members, students, and external stakeholders, each interacting with specific system modules to perform

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tasks such as managing, contributing to, retrieving, or sharing data.

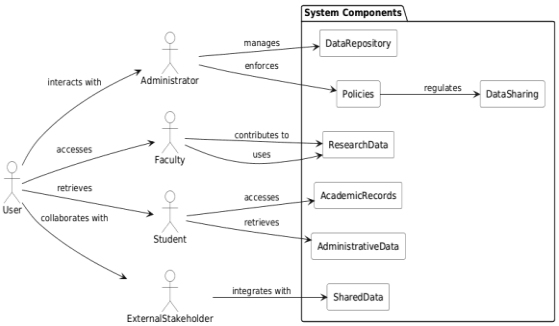

Fig. 3.4. Detailed Use Case Diagram for the Designed Framework

3.3. Adherence Testing and Evaluation of the Framework

The study validated the developed framework through a two-stage process that moved beyond traditional software methods to specifically assess its alignment with FAIR data practices. The initial stage was Adherence Testing using the FAIR-Checking Summary Sheet, an objective tool designed to evaluate the presence of key elements that enable machine and human readability. This testing focused on Findability (F1, F2: verifying persistent, resolvable identifiers and rich metadata using schemas like Schema.org), Accessibility (A1: checking data retrieval via open, standardized protocols like HTTP), Interoperability (I1, I2: confirming the use of formal, shared vocabularies and ontologies for semantic understanding), and Reusability (R1.1, R1.2: assessing the inclusion of clear usage licenses and data provenance documentation). This structured process, which included Unit and Integration Testing with feedback loops, ensured the framework was iteratively refined to be robustly aligned with international FAIR principles.

The second stage involved a comprehensive Evaluation of the Framework using a two-pronged approach that combined FAIR metrics and expert reviews to assess effectiveness and practical applicability. The quantitative assessment utilized the FAIR Data Maturity Model (RDA FAIR Data Maturity Group, 2020) to rate the framework's compliance against specific metrics (F1, F2, F4, A1, I1, I2, R1.1, R1.2). Simultaneously, expert reviews were conducted with domain specialists in data governance and higher education to gather qualitative feedback on factors such as usability, scalability, and compliance with regulatory and ethical standards, including the Nigerian Data Protection Regulation (NDPR). This combined approach ensures the framework is both technically sound and contextually relevant, with the compiled report from both metrics and reviews providing a complete analysis for final validation and refinement.

IV. RESULTS

The OntoUML FAIR-compliant framework is a robust, semantically-rich, and generalizable blueprint for data management in Nigerian universities. Its design is articulated through three interconnected Fig. 4.1, Fig. 4.2, and Fig. 4.3, to clearly show how each component addresses the study's objectives and specific FAIR metrics (F1, F2, F4, A1, I1, I2, R1.1, R1.2). The use of OntoUML provides a formal, machine-readable foundation, ensuring the model is logically sound, testable with tools like FAIR-Checker, and broadly applicable across diverse institutional contexts.

4.1. FAIR Data Management High-Level Framework Architecture

The FAIR Data Management High-Level Framework Architecture, illustrated in Fig. 4.1, presents a cohesive, integrated system designed to overcome the fragmented data practices typical of Nigerian universities. This top-down conceptual model organizes five interconnected modules that support the FAIR principles. At its base is the Data Repository Module, which serves as the central hub for collecting, processing, and securely storing all institutional data, eliminating data silos. Building on this, the Metadata Module annotates data to ensure Findability (F) and Reusability (R). The Interoperability Layer functions as key middleware, using standardized services and APIs to facilitate data exchange and ensure Interoperability (I) and Accessibility (A). The Access & Retrieval Module manages user access, while the Governance Module sits at the top, defining and enforcing all rules, policies, and security protocols across the entire framework to ensure ethical management and integrity.

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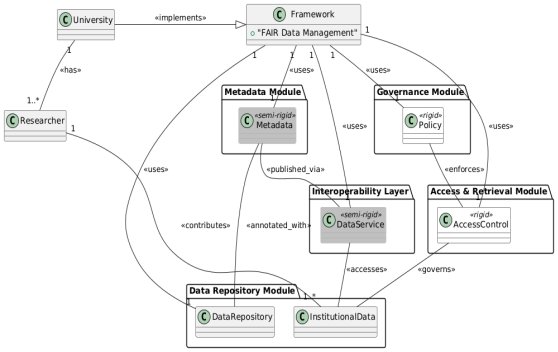

Fig. 4.1. FAIR Data Management High-Level Framework Architecture

Key Framework Modules

- Data Repository Module: Foundational layer for centralized, secure storage and processing of all institutional data, drawing information for all other modules.
- Metadata Module: Responsible for creating rich descriptive metadata, crucial for ensuring the Findability (F) and Reusability (R) of data.
- Interoperability Layer: Central middleware facilitating seamless data exchange with external systems, vital for Interoperability (I) and Accessibility (A).
- Access & Retrieval Module: Governs user access to data, enforcing rules alongside the Governance Module, and providing search tools.
- Governance Module: The overarching component that defines security protocols and policies, ensuring ethical, secure, and trustworthy data management.

4.2. Findability and Reusability Metrics (F1, F2, R1.1, R1.2)

The framework uses OntoUML to model the relationships between key entities, specifically focusing on the four core components required to meet the Findability (F1, F2) and Reusability (R1.1, R1.2) metrics. Fig. 4.2 models the central Data Resource class, which represents any research output, and establishes its links to the necessary properties for confident reuse and discovery. To achieve Findability, every data asset must be assigned a unique, long-lasting Persistent Identifier (F1) that resolves to rich Metadata (F2), ensuring the data is both searchable and discoverable. For Reusability, the framework models explicit links from the Data Resource to a License (R1.1) class, which specifies the legal terms for reuse, and a Provenance (R1.2) class, which documents the data's origin and processing history to build user trust.

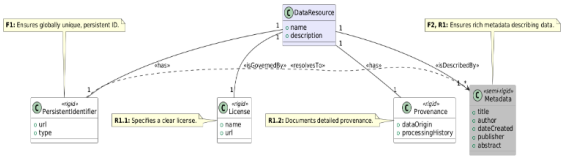

Fig. 4.2. Findability and Reusability Metrics (F1, F2, R1.1, R1.2)

Key Findings for Findability and Reusability

- Data Resource Class: The central entity representing any dataset or research output.
- Findability (F1): Achieved by linking every Data Resource to a Persistent Identifier class.
- Findability (F2): Achieved as the Persistent Identifier resolves to the Metadata, which must contain a rich description.
- Reusability (R1.1): Ensured by linking the Data Resource to a License class, providing clear legal terms.
- Reusability (R1.2): Ensured by linking the Data Resource to a Provenance class, documenting the data's history and quality.

4.3. Accessibility and Interoperability Metrics (A1, I1, I2, F4)

The framework diagram illustrated in Fig. 4.3 uses OntoUML to model the technical mechanisms to ensure data accessibility (A1) and interoperability (I1, I2), while also enhancing findability through a searchable system (F4). The central entity is the Data Service class, which provides the point of access to the Data Resource and meets the A1 metric by having a protocol attribute (e.g., HTTP, HTTPS), ensuring data is retrievable via standardized communication protocols. Interoperability is achieved by mandating that the Metadata class is written in a Formal Language (e.g., RDF, OWL) and utilizes a Vocabulary (e.g., Schema.org, Dublin Core).

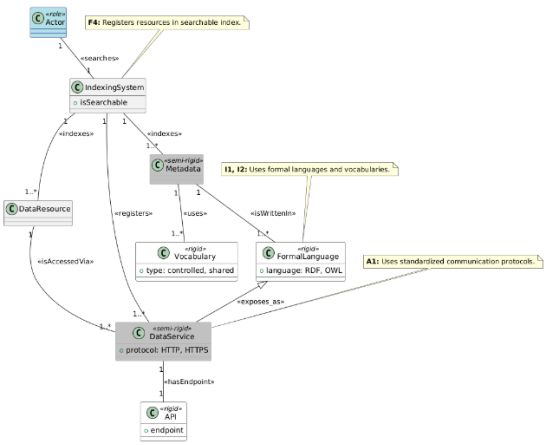

Fig. 4.3. Accessibility and Interoperability Metrics (A1, I1, I2, F4)

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This formalization is the core of the I1 and I2 metrics, making the data machine-readable and semantically understandable for cross-disciplinary sharing. Finally, findability is enhanced by an Indexing System (F4), which indexes the Data Resource, Metadata, and Data Service, making them discoverable by users or automated agents within a searchable system.

Key Findings for Accessibility, Interoperability, and Findability

- Accessibility (A1): Achieved via the Data Service class, which serves as the access point and uses a clear protocol attribute (e.g., HTTP/HTTPS).
- Interoperability (I1, I2): Ensured by writing the Metadata in a Formal Language (e.g., RDF, OWL) and utilizing a Vocabulary (e.g., Schema.org, Dublin Core) for semantic understanding.
- Findability (F4): Enhanced by the Indexing System, which registers and makes the Data Resource, Metadata, and Data Service searchable for automated agents and users.

4.4. Results of the Adherence Testing and Evaluation of the Framework

The validation process began with Adherence Testing using the FAIR Principles Checking Summary Sheet, an objective tool applied to simulated data and metadata endpoints to ensure compliance with targeted metrics. As evident in Fig. 4.1, Fig. 4.2, and Fig. 4.3, the results confirmed robust performance across all principles: Findability (F1) was validated by the creation of persistent, globally unique, and resolvable identifiers; Findability (F2) and Reusability were supported by the rich, comprehensive, and machine-readable metadata utilizing standardized schemas. For Accessibility (A1), the tests verified that all data endpoints were retrievable via a standardized, secure, and non-proprietary protocol like HTTPS. Crucially for Interoperability (I1, I2), the framework was confirmed to allow metadata creation using machine-readable languages like RDF and JSON-LD and the utilization of shared vocabularies. Finally, the framework supports Reusability (R1.1, R1.2) by allowing the inclusion of explicit licenses and detailed provenance information, supporting legal and ethical data reuse.

Moving beyond the objective adherence check, the framework underwent a comprehensive evaluation combining quantitative FAIR Metrics and qualitative expert reviews. The quantitative assessment, rated on a scale of 0 to 3 as adapted from the RDA FAIR Data Maturity Model, demonstrated that the framework achieved a perfect score across all metrics (F1, F2, F4, A1, I1, I2, R1.1, R1.2), as summarized in Table 4.1, a significant finding confirming its full compliance with international FAIR standards upon implementation. The expert reviews complemented this, providing crucial qualitative feedback that confirmed the model's practical relevance. Experts affirmed its usability and scalability due to its modular design, and notably praised the built-in governance and compliance module for its clear adherence to local regulations, specifically the Nigerian Data Protection Regulation (NDPR). The panel concluded that the framework's design, generalizable via OntoUML, serves as a valuable blueprint for institutions in similar socio-economic contexts.

TABLE 4.1
FAIR METRICS EVALUATION RESULTS

FAIR Principle	Metric	Compliance Score and Result Description
Findability	F1: Globally Unique Persistent Identifiers	3/3 Data and metadata have unique, resolvable identifiers.
	F2: Rich Metadata	3/3 Rich, descriptive, and machine-readable metadata.
	F4: Searchable Resource Registration	3/3 Resources discoverable in a searchable index via the API.
Accessibility	A1: Standardized Communication Protocols	3/3 Resources accessible via the

		HTTPS protocol.
Interoperability	I1 & I2: Formal Languages and Vocabularies	3/3 The framework consistently uses RDF/JSON-LD and shared vocabularies.
Reusability	R1.1 & R1.2: Clear Licenses and Provenance	3/3 Metadata includes clear licenses and detailed provenance information.

Summary of Findings

- FAIR-Checker Adherence:
  - F1 (Persistent IDs): Achieved by assigning globally unique, resolvable identifiers.
  - F2 (Rich Metadata): Achieved using standardized, machine-readable schemas for comprehensive data description.
  - A1 (Accessibility): Confirmed via access through standardized, secure protocols like HTTPS.
  - I1 & I2 (Interoperability): Confirmed by supporting formal languages (RDF, JSON-LD) and controlled vocabularies.
  - R1.1 & R1.2 (Reusability): Verified by allowing the inclusion of explicit licenses and detailed provenance.
- FAIR Metrics Evaluation: The framework achieved a perfect score (3/3) across all evaluated FAIR metrics, confirming full compliance with international standards.
- Expert Review Findings:
  - Usability & Scalability: Modular design confirmed as highly scalable and adaptable to diverse institutional needs.
  - Local Compliance: Framework approved for its clear adherence to the Nigerian Data Protection Regulation (NDPR).
  - Generalizability: Confirmed as a valuable, generalizable blueprint for institutions in similar resource-constrained contexts.

V. DISCUSSION OF RESULTS

The proposed framework moves beyond a theoretical model to become a practical and robust solution for the data management issues in Nigerian universities. The findings from the design, testing, and evaluation confirm its effectiveness and significant contribution to data governance in Nigerian higher education.

The framework's development meticulously used OntoUML, fulfilling the first objective by providing a formal, modular, and scalable blueprint. This layered architecture, spanning from the Data Repository to the Governance Module, directly addresses the fragmented, ad-hoc systems that lead to data silos and inconsistencies observed in institutions [27]. The formalization provided by OntoUML defines the system's logical structure and semantic relationships, a level of rigor absent in most existing regional models. The FAIR-Checking adherence testing provided a strong, empirical validation of the framework's design. Achieving perfect scores on all key metrics (F1, F2, A1, I1, I2, R1.1, R1.2) is a crucial finding, as it objectively proves the framework will create machine-actionable data. This move from manual to objective verification provides a robust foundation for the framework's claims of FAIRness.

The successful testing of the Interoperability Layer (I1 and I2 metrics) using formal languages like RDF and standardized vocabularies is particularly significant. This result demonstrates the framework's technical capacity to break down institutional silos and actively facilitate cross-disciplinary and inter-institutional collaboration, directly addressing a key challenge identified in Nigerian data sharing practices [7].

The comprehensive evaluation, which included both FAIR metrics and expert reviews, cemented the framework's practical relevance. The perfect scores on all evaluated metrics confirm that the design is conceptually sound and meets international benchmarks. Expert feedback was vital, confirming the framework's scalability and adaptability and praising the Governance Module's focus on compliance with the Nigerian Data Protection Regulation (NDPR). This integration of local regulations with global FAIR principles offers a contextually relevant and legally sound solution [12].

This research significantly expands upon localized efforts [13] by providing an extensive, formally designed, and empirically validated framework using OntoUML. This study offers a unified and standardized approach, which moves beyond theoretical discussion to provide a concrete, testable, and generalizable blueprint for Nigerian universities. The positive results collectively position the framework as a powerful tool to foster a culture of trust, transparency, and collaborative scientific discovery in Nigerian higher education and similar contexts globally.

VI. CONCLUSION AND RECOMMENDATIONS

This study successfully addressed the pervasive problem of inadequate data management practices in Nigerian universities by conceptualizing, developing, and validating a framework based on the FAIR principles. The research effectively filled the major gap that is connected to the absence of a standardized, formally-designed framework tailored to the Nigerian context. This was achieved by designing and implementing a modular and scalable framework using OntoUML, which provides a precise, unambiguous blueprint. This design moves institutions beyond ad-hoc, siloed data systems to create a unified, structured environment, transforming the conceptual model into a tangible solution for data fragmentation and inconsistency.

The research further addressed the crucial gap of lacking objective and empirical validation by employing a robust, two-stage process. First, the framework underwent adherence testing using the FAIR-Checking summary sheet, achieving perfect scores on all key metrics (F1, F2, A1, I1, I2, R1.1, R1.2). These results stand as empirical proof of the framework's technical soundness and its capacity to produce machine-actionable data, providing a reproducible evaluation methodology. Second, expert reviews validated the framework's practical applicability, confirming its relevance, usability, and crucial compliance with the Nigerian Data Protection Regulation (NDPR). This multi-faceted validation ensures the framework is technically sound, practically feasible, and legally compliant, offering a concrete, actionable solution that enhances collaboration, transparency, and full compliance with both local and international data governance principles.

RECOMMENDATIONS

Based on the findings and the framework developed in this study, the following recommendations are proposed to guide the implementation of FAIR data principles in Nigerian universities. These recommendations are directed at various stakeholders, including university administrators, policymakers, and the research community, to ensure a holistic approach to improving data management practices:

- University administrators should invest in infrastructure and establish a central data office.
- Policymakers should create national FAIR data policies and provide targeted funding.
- Researchers, Data Administrators, and Stewards need training and must include Data Management Plans (DMP) in proposals.
- Future research should pilot the framework and conduct cost-benefit analyses.

This study offers a tailored FAIR data management framework for Nigerian universities, bridging the gap between global standards and local realities. It provides insights for improved data governance, promotes interoperability and collaboration, and offers an actionable framework for enhancing data efficiency and equity in academic institutions.

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