Nanotechnology Policy Adoption in Sub-Saharan Africa: A Survey of Government Sectors and Higher Institutions Across Nigeria's Six Geopolitical Zones

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Abstract

Nanotechnology presents opportunities for scientific advancement, industrial diversification, healthcare innovation, and environmental management, yet its effective governance depends on institutional capabilities that remain unevenly documented across Sub-Saharan Africa. This study examines the policy arrangements, administrative responsibilities, and research governance conditions relevant to nanotechnology adoption in Nigeria's six geopolitical zones. Drawing on a critical synthesis of scholarly literature published through 2021, it evaluates national policy development, governmental coordination, university participation, institutional readiness, stakeholder awareness, and implementation constraints. A comparative survey framework is proposed for examining government agencies and higher institutions through structured questionnaires, institutional interviews, and documentary verification. Assessment indicators include formal mandates, research financing, technical infrastructure, personnel competencies, safety protocols, interagency cooperation, and evidence of operational implementation.

The synthesis identifies fragmented responsibilities, resource limitations, uneven research capabilities, and inadequate mechanisms for monitoring policy commitments as important governance concerns. It further establishes that scientific publication activity, stated policy aspirations, and laboratory presence cannot independently demonstrate institutional adoption. International and African experiences underscore the importance of risk-sensitive oversight, collaborative research arrangements, transparent decision-making, and contextually appropriate capacity development. However, the available literature does not support empirical rankings of adoption across Nigeria's geopolitical zones; such comparisons require standardized primary data and corroborating institutional records.

The study recommends a coordinated national governance mechanism, clearer regulatory mandates, shared research infrastructure, targeted professional training, and periodic institutional

assessments. Future empirical investigations should evaluate regional implementation patterns and measurable developmental outcomes. These measures would strengthen accountable policymaking while supporting equitable and responsible nanotechnology development across governmental and academic institutions, with explicit attention to institutional differences and uncertainty.

Keywords: Nanotechnology policy; Institutional governance; Policy adoption; Higher education institutions; Regulatory harmonization; Sub-Saharan Africa.

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1. Introduction

1.1 Background and Evolution of Nanotechnology Policy

Nanotechnology has evolved from a specialized field of nanoscale investigation into a strategic domain of science, industrial innovation and public policy. By enabling the manipulation and characterization of materials at exceptionally small dimensions, it offers potential applications in medicine, agriculture, water treatment, energy systems and advanced manufacturing. Its emergence as a policy concern reflects the recognition that scientific capability alone cannot secure socially beneficial innovation. Governments must also coordinate research investment, establish oversight arrangements, develop technical expertise and address uncertainty surrounding environmental and human exposure. Early governance debates consequently questioned whether established regulatory systems could adequately respond to rapidly evolving nanoscale applications, particularly when commercial development progressed faster than institutional deliberation (Whitman, 2007).

The international policy landscape subsequently moved toward integrated approaches combining scientific advancement with responsible development. National research programmes increasingly linked public funding to innovation priorities, interdisciplinary collaboration and assessment of societal consequences. The governance framework articulated by Roco et al. (2011) emphasized coordination among governments, research institutions, industry and civil society, demonstrating that responsible nanotechnology development requires more than isolated laboratory achievements. This evolution also challenged conventional distinctions between research promotion and regulatory supervision because public authorities frequently perform both functions.

Regulatory debates further exposed disagreement about the appropriate balance between mandatory controls and voluntary standards. Rather than assuming that either approach could independently resolve uncertain risks, Malloy (2011) examined the case for adaptive regulatory arrangements capable of responding to emerging evidence. Similar institutional concerns arise where nanotechnology applications intersect established administrative jurisdictions, making

cooperation among agencies responsible for health, environmental protection, industrial development and scientific research essential. Karkkainen (2011) identified interagency coordination as a central consideration in assessing oversight of nanobiotechnology, with implications for policy coherence across government sectors.

Policy evolution has also involved growing recognition of public participation and institutional legitimacy. Stakeholder deliberation can encourage knowledge exchange and mutual accountability, although participation arrangements may reproduce exclusions when decision-making becomes concentrated within established networks. Research on governance dialogues demonstrated how trust influences cooperation among regulators, scientists and other stakeholders (Åm, 2011). Anticipatory approaches subsequently placed greater emphasis on foresight, engagement and integration of societal perspectives before technological pathways become entrenched. Such thinking positions higher institutions as contributors not only to technological discoveries but also to public consultation, risk assessment and policy learning (Guston, 2014).

Within Africa, nanotechnology policy development has been conditioned by unequal research infrastructure, funding capacity and institutional coordination. South Africa offers an instructive example of attempts to align nanoscale research with national development needs, including water provision and healthcare. Nevertheless, the country's emerging research agenda highlighted the importance of environmental, health and safety investigations alongside investments in laboratories and human capital (Musee, Brent & Ashton, 2010). This illustrates the relevance of examining policy adoption as an institutional process rather than merely documenting the presence of research facilities.

For Nigeria, the broader challenge of translating technological possibilities into implementable institutional programmes is visible across adjacent innovation sectors. Research on solar integration in small manufacturing enterprises illustrates the importance of technological adaptation to local operational conditions and resource constraints (Sunday & Omoegun, 2018). Likewise, modelling hydrogen integration within national grids underscores the systems-level planning required to integrate emerging technologies into existing infrastructure (Adeniji et al., 2019). These perspectives inform the present review's attention to governmental preparedness, university research capacity and coordination mechanisms across Nigeria's six geopolitical zones.

1.2 Nanotechnology Governance in Sub-Saharan Africa

Nanotechnology governance in Sub-Saharan Africa reflects interactions between national innovation ambitions, regulatory capacity and institutional arrangements supporting scientific research. Although governments increasingly recognize nanoscale technologies as potential contributors to health, agriculture, environmental management and industrial diversification, their policy responses differ substantially. Governance encompasses research financing, technical standards, occupational safeguards, commercialization mechanisms and institutional accountability. These dimensions require coordinated public administration rather than reliance on research activity as an indicator of adoption.

Evidence from Nigeria identifies expanding interest in green nanotechnology alongside persistent constraints involving research funding, specialized infrastructure, workforce development and policy coordination. The relationship between laboratory investigation and national development therefore depends on institutions capable of converting scientific capability into funded programmes, appropriate regulatory provisions and sustained university–industry collaboration (Elegbede & Lateef, 2019).

Regional governance challenges also concern implementation quality. An examination of technological transformation and economic integration within the Southern African Development Community emphasizes ethical leadership, institutional responsibility and difficulties fulfilling collective policy commitments. These considerations are pertinent where nanotechnology initiatives depend on public investment and cross-border collaboration (Enaifoghe, Dlamini & Agwuna, 2020).

Comparative experience from India indicates that governance priorities are shaped by national development agendas and political understandings of technological progress. Consequently, imported policy models cannot automatically accommodate the economic structures and institutional needs of African countries (Beumer, 2019). Research across Sub-Saharan African innovation systems similarly identifies fragmented responsibilities, inadequate organizational capabilities and weak relationships among government, universities and industry as obstacles to effective policy implementation (Twiringiyimana, Daniels & Chataway, 2021).

International discussions additionally emphasize regulatory learning, anticipatory assessment and trusted environments supporting exchanges between innovators and oversight authorities. Such mechanisms can facilitate responsible innovation without assuming that emerging technologies are uniformly understood or controlled (Soeteman-Hernández et al., 2021). For Nigeria, examining government sectors and higher institutions across six geopolitical zones can clarify differences between stated priorities and operational adoption. Relevant measures include institutional mandates, dedicated budgets, research facilities, technical training, stakeholder participation and mechanisms for environmental and health risk oversight. These indicators provide a coherent basis for comparing policy implementation while recognizing variation in regional institutional capacity and access to scientific resources.

1.3 Research Problem and Knowledge Gaps

Nanotechnology is increasingly recognized as a potential driver of industrial innovation, healthcare improvement, environmental remediation, and agricultural productivity. Nevertheless, the extent to which this potential has translated into coherent public policy and operational institutional commitments across Sub-Saharan Africa remains insufficiently understood. In Nigeria, discussions of technological advancement often emphasize research outputs and prospective applications without systematically examining whether government agencies and higher institutions possess the mandates, resources, coordination mechanisms, and oversight procedures required for effective nanotechnology policy adoption.

A central research problem concerns the absence of comparable evidence on how policy awareness, institutional preparedness, and implementation practices differ across Nigeria's six geopolitical zones. Existing accounts rarely distinguish formal policy endorsement from practical adoption, thereby obscuring differences between strategic intentions and measurable institutional action. Furthermore, fragmented information concerning research financing, specialized infrastructure, regulatory responsibilities, workforce competencies, and university–government partnerships limits understanding of the conditions shaping adoption. Insufficient attention to regional inequalities may also conceal geographic concentrations of research capacity and uneven access to collaborative opportunities.

Additional knowledge gaps concern how institutional actors interpret emerging technological risks, incorporate environmental and occupational safeguards, and evaluate the relevance of international governance frameworks to local priorities. Without an integrated institutional assessment, policymakers lack a reliable basis for identifying adoption barriers, comparing institutional performance, and prioritizing interventions. This study therefore examines policy adoption across government sectors and higher institutions, emphasizing regional variation, governance capacity, implementation constraints, and opportunities for coordinated, context-sensitive development of nanotechnology policy in Nigeria.

1.4 Study Objectives, Scope, and Significance

This study examines the adoption of nanotechnology policy within government sectors and higher institutions across Nigeria's six geopolitical zones, situating national experiences within the wider governance landscape of Sub-Saharan Africa. Its primary objective is to assess how institutional awareness, policy commitments, administrative arrangements, and research capabilities influence the translation of nanotechnology priorities into operational practice. Specifically, the study seeks to identify existing governance mechanisms, compare levels of institutional preparedness, examine implementation barriers, and determine opportunities for strengthening coordination between public authorities and higher education institutions.

The scope encompasses federal and subnational government bodies with responsibilities relevant to science, technology, innovation, education, industry, health, and environmental protection, alongside universities and other higher institutions engaged in research or technological development. Geographical coverage extends to the North Central, North East, North West, South East, South South, and South West zones. The analysis considers policy awareness, funding arrangements, technical infrastructure, human resource capacity, research partnerships, and safeguards for responsible innovation. It does not presume that the existence of research activity demonstrates formal policy adoption.

The study is significant because systematic institutional comparison can illuminate regional disparities that national policy narratives may overlook. Its findings are intended to inform evidence-based priority setting, strengthen institutional accountability, and support context-sensitive frameworks for nanotechnology governance. By distinguishing stated commitments from

implementation capacity, the research can assist policymakers, university administrators, and research stakeholders in designing practical interventions that advance equitable participation, responsible technological development, regulatory coherence, and sustained collaboration across Nigeria's innovation system.

2. Nanotechnology Policy Frameworks and Institutional Governance

2.1 National Policy Development and Regulatory Structures

National nanotechnology policy development requires coordinated institutional arrangements that connect scientific priorities, regulatory responsibilities and implementation mechanisms. Effective frameworks establish research objectives, allocate administrative authority, define technical standards and provide procedures for managing environmental, occupational and public health risks. In Sub-Saharan Africa, these requirements intersect with differing national innovation capabilities, public financing arrangements and regulatory infrastructures. Consequently, evaluating policy adoption demands attention to the relationship between formal governmental commitments and institutional capacity to operationalize them.

South Africa provides a regional illustration of structured nanotechnology development through its National Nanotechnology Strategy, introduced in 2005. Subsequent research documented expanding scientific publications, collaboration networks and institutional participation, demonstrating how strategic governmental intervention can influence national research activity (Makhoba & Pouris, 2017). However, research expansion alone cannot establish whether regulatory enforcement, equitable resource distribution or commercialization arrangements have matured correspondingly.

International regulatory scholarship identifies the importance of clearly defined nanomaterial classifications, standardized characterization procedures and proportionate safety requirements. Effective regulation must address technological diversity without imposing uniform obligations on materials exhibiting different properties and exposure pathways. Clausen & Hansen (2018) emphasize foundational regulatory principles intended to improve consistency, transparency and protection. Complementing this perspective, comparative assessments reveal persistent difficulties harmonizing terminology, testing methodologies and regulatory jurisdictions across countries (Allan et al., 2021).

The development of operational oversight mechanisms further requires evidence-based risk assessment systems. Regulatory authorities must determine appropriate testing obligations, manage scientific uncertainty and establish procedures for reviewing emerging safety information. Existing assessment frameworks differ considerably in scope and applicability, creating practical difficulties for institutions operating with limited analytical resources (Oomen et al., 2018).

Within Nigeria, technology governance provides relevant institutional lessons concerning regulatory compliance, accountability and administrative coordination. Evidence from insurance-sector governance highlights the significance of structured control frameworks, organizational

responsibility and compliance monitoring in technology-intensive operations (Fadero et al., 2018). Comparable administrative principles can inform nanotechnology oversight involving government ministries, research councils and higher institutions.

Infrastructure considerations also influence the feasibility of implementing national technology policies. Research examining hybrid solar installations identifies financing, technical optimization and operational conditions relevant to technology deployment in developing economies (Sunday & Omoegun, 2019). Geospatial assessments of rural healthcare accessibility likewise demonstrate the importance of geographical conditions when evaluating the distribution and accessibility of public services (Alaka, Ajayi & Bolaji, 2020).

2.2 Governmental Roles in Nanotechnology Policy Implementation

Governmental involvement in nanotechnology policy implementation extends from strategic priority setting to institutional coordination, regulatory supervision and evaluation of research outcomes. Public authorities establish the conditions under which nanoscale innovations can progress from scientific investigation to commercially and socially beneficial applications. Such responsibilities require consistent funding arrangements, competent administrative structures and accountability mechanisms connecting scientific objectives with national development priorities.

Regulatory leadership is particularly important where scientific uncertainty complicates conventional administrative decision-making. Governments must determine suitable oversight instruments, clarify institutional mandates and balance precautionary requirements against innovation opportunities. Evidence from emerging technology regulation demonstrates that public agencies frequently retain conventional supervisory powers despite growing interest in flexible governance arrangements (Stokes, 2013). Comparative assessments of European and American nanomaterial policies similarly establish the continuing importance of state-directed rulemaking in responding to technological risks (Justo-Hanani & Dayan, 2014).

Effective policy implementation additionally requires mechanisms for stakeholder engagement and transparent institutional communication. Government agencies can strengthen regulatory legitimacy by involving researchers, industry representatives, civil society organizations and affected communities in policy deliberations. Participatory approaches facilitate consideration of competing expectations while improving opportunities for institutional learning (Russell, 2013).

Public-sector planning must also anticipate emerging technological applications and associated uncertainties. Scenario-based assessment provides opportunities to examine regulatory preparedness, identify governance weaknesses, and develop adaptive intervention strategies before technological deployment becomes widespread (Read et al., 2016). Alongside these responsibilities, governmental research funding can support interdisciplinary collaboration and engagement with societal concerns, although institutional incentives must encourage substantive participation rather than procedural compliance alone (Corley & Guston, 2019).

African experiences emphasize the significance of administrative responsiveness and coordinated governmental action. South Africa's pandemic response illustrates how institutional capacity, policy communication and resource mobilization influence responses to complex national challenges (Ikwegbue et al., 2021). Within Nigeria, emerging energy technologies similarly present coordination requirements involving technical systems, regulatory arrangements and stakeholder participation, as illustrated by blockchain-enabled renewable microgrid trading models (Shittu et al., 2021).

2.3 Higher Education Institutions and Research Governance

Higher education institutions occupy a central position in nanotechnology governance because they generate scientific knowledge, train personnel and translate research priorities into technological capabilities. Their responsibilities extend to laboratory safety, research ethics, intellectual property management and the administration of publicly funded programmes. Institutional effectiveness depends on governance arrangements connecting academic autonomy with transparent oversight and national innovation objectives.

The relationship between universities, government and industry provides an analytical foundation for understanding these responsibilities. The Triple Helix framework conceptualizes innovation as an evolving interaction among institutions that produce knowledge, regulate technological activity and commercialize research outputs (Etzkowitz & Leydesdorff, 2000). For nanotechnology, such interaction requires agreements governing shared facilities, technical expertise, funding obligations and research dissemination.

International experience demonstrates that targeted policy initiatives can reshape university research incentives. An assessment of the United States National Nanotechnology Initiative identified increased industry-to-university knowledge flows alongside narrower research trajectories, indicating that public investment may produce intended and unintended effects (Jung & Lee, 2014). Research priority setting therefore needs safeguards against excessive concentration on commercially attractive applications. Studies of American and British nanotechnology programmes emphasize incorporating societal considerations into institutional decisions about research directions and resource allocation (Fisher & Maricle, 2015).

African higher education systems face governance challenges involving equipment costs, professional development and continuity of research financing. Evidence from South African university partnerships demonstrates that international collaboration can strengthen researcher competencies and institutional capacity when supported by coordinated programmes (Frantz et al., 2014). Research leadership is equally consequential: African institutional assessments identify strategic direction and managerial capabilities as important conditions for building durable research environments (Owusu et al., 2017).

Administrative effectiveness also influences how universities implement specialized research programmes. Evidence from universities in Oyo State associates professional attributes of administrative personnel with organizational performance, drawing attention to operational

functions supporting academic governance (Onche, Adenekan & Sabboh, 2021). Such functions include documentation, procurement coordination, grant administration and communication across institutional units.

Universities increasingly engage in entrepreneurial activity, but commercialization requires governance that protects research integrity while facilitating knowledge transfer (Etzkowitz et al., 2000). Across Nigeria's six geopolitical zones, institutional assessment should examine dedicated nanotechnology centres, researcher training, laboratory accreditation, safety procedures, partnerships and research funding. Distinguishing established structures from functioning practices can reveal whether higher institutions possess the capacity to participate effectively in national nanotechnology policy implementation. Comparative assessment should also consider equitable access to facilities, consistent reporting obligations and opportunities for collaboration across dispersed institutions.

3. Nanotechnology Policy Adoption Across Nigeria's Geopolitical Zones

3.1 Regional Disparities in Institutional Policy Adoption

Regional disparities in nanotechnology policy adoption arise when scientific infrastructure, institutional financing, and administrative capabilities are distributed unevenly. Within Nigeria, the six geopolitical zones provide a geographical framework for examining whether government agencies and higher institutions possess comparable opportunities to interpret, fund and implement emerging technology policies. Their differences should be evaluated through documented institutional indicators rather than assumptions that geographical location determines technological performance.

Research on African research and development demonstrates considerable variation in financing and scientific capacity, highlighting the influence of investment patterns on opportunities for specialized research (Simpkin et al., 2019). International bibliometric evidence further associates nanotechnology productivity with research funding and collaborative networks, suggesting that regional analysis should consider the distribution of institutional resources alongside publication activity (Aleixandre-Tudó et al., 2020).

Nigeria-specific scientometric research identifies concentrations of nanotechnology publications and institutional contributions, indicating that scientific participation differs across organizations (Lateef et al., 2021). However, publication output cannot independently establish whether universities have adopted formal nanotechnology governance policies. Adoption must also be assessed through approved institutional strategies, dedicated budgets, safety procedures, personnel assignments, and documented interagency relationships.

Geographical accessibility introduces an additional consideration. Assessments of drainage structures in southwestern and north-central Nigeria illustrate how place-based infrastructure evaluation can reveal variation within public service environments (Bolaji et al., 2019). Network analysis of emergency response access in Kwara State likewise demonstrates the analytical value

of examining spatial coverage rather than relying exclusively on administrative totals (Tiamiyu, Alaka & Ajayi, 2021). These approaches can inform institutional survey design without establishing nanotechnology adoption.

Collaborative capacity also matters. Research involving Nigerian universities in northern locations identified barriers to knowledge exchange between academic institutions and firms (Alkali, 2021). A wider survey spanning the six zones associated enabling policies and university–industry linkages with innovative behaviour, supporting the inclusion of institutional partnerships among comparative indicators (Dutse et al., 2021). Across selected Sub-Saharan African countries, collaboration patterns likewise demonstrate why research networks should be examined alongside local institutional capacity (Onyancha, 2021).

The illustrative assessment matrix below specifies comparable evidence to collect in each zone. Identical indicators would permit systematic comparison while accommodating differences in institutional mandates, disciplinary specialization and local research priorities. Survey responses should be triangulated with policy documents, budget records and institutional research inventories. Distinguishing confirmed adoption, partial implementation and absent documentation would prevent unsupported regional rankings. Such differentiation is essential because institutional awareness, research productivity and operational policy adoption represent distinct analytical dimensions. An evidence-based assessment can subsequently identify where resource constraints, administrative fragmentation or limited collaborative opportunities impede implementation. These distinctions would strengthen the interpretation of geographical disparities and guide the formulation of institutionally appropriate policy interventions.

Table 1. Illustrative framework for assessing regional disparities in nanotechnology policy adoption across Nigeria's six geopolitical zones

Geopolitical zone	**Institutional coverage**	**Principal assessment indicators**
North Central	Government agencies and higher institutions	Research financing, policy documentation and interagency coordination
North East	Government agencies and higher institutions	Institutional preparedness, laboratory access and technical personnel
North West	Government agencies and higher institutions	Policy awareness, research partnerships and capacity development
South East	Government agencies and higher institutions	Research commercialization, institutional mandates and innovation support
South South	Government agencies and higher institutions	Environmental safeguards, industry partnerships and research infrastructure
South West	Government agencies and higher institutions	Nanotechnology research capacity, regulatory procedures and institutional collaboration

Source: Author-developed assessment framework informed by the literature reviewed. The indicators are proposed dimensions for investigation, not established findings or verified regional specializations. All indicators should be evaluated in every zone using consistent measures.

3.2 Institutional Readiness, Awareness, and Implementation Barriers

Institutional readiness for nanotechnology policy adoption encompasses the administrative, scientific, and organizational capabilities required to translate policy intentions into functioning research and oversight arrangements. Within Nigeria's six geopolitical zones, readiness cannot be inferred solely from university research activity or governmental statements. It requires evidence of approved institutional mandates, sustained financing, laboratory infrastructure, qualified personnel and procedures for managing nanomaterial risks.

Human capital constitutes a critical dimension of implementation. A conceptual model of talent development across distributed operations illustrates the importance of aligning professional competencies with organizational responsibilities and continuous capacity building (Falemi, Akhigbe & Akin-Oluyomi, 2020). Evidence from a rural South African university similarly demonstrates that researcher development depends on institutional incentives, postgraduate supervision and targeted support, rather than equipment investment alone (Singh, 2015). For Nigerian higher institutions, comparable measures would include specialist training opportunities, technical staffing, shared research facilities and administrative support for grant management.

Readiness also depends on reliable supporting infrastructure. Research on grounding optimization in emerging electricity markets illustrates the technical planning required to maintain dependable systems serving advanced operations (Shittu et al., 2020). Nanotechnology laboratories require more specific provisions, including stable electricity, instrument maintenance, safe material storage, and appropriate waste management. Their availability should be assessed directly rather than assumed from general institutional resources.

Awareness presents a distinct barrier because stakeholders may differ in their familiarity with nanoscale applications and associated uncertainties. A comparative study of public, academic, governmental and business attitudes found variation in risk perceptions and trust, highlighting the importance of differentiated engagement strategies (Capon et al., 2015). Citizen-science research likewise linked limited knowledge with less favourable attitudes, supporting accessible communication and opportunities for informed participation (Joubert et al., 2020). Broader comparisons between developed and developing countries indicate that cultural expectations, trust and information channels shape attitudes toward nanotechnology (Rathore & Mahesh, 2021).

Implementation additionally requires credible monitoring and assessment. South African experience shows that investments in research centres, scientific training and collaborative networks do not automatically establish measurable developmental impact (Saidi & Douglas, 2017). Frameworks addressing nanomaterial risk governance therefore emphasize coordinated assessment, communication and mitigation tools supported by institutional accountability (Isigonis et al., 2019).

4. Survey Methodology and Comparative Institutional Assessment

A comparative assessment of nanotechnology policy adoption across Nigeria's six geopolitical zones requires a design capable of distinguishing institutional awareness, formal authorization and implementation. A proposed convergent mixed-methods survey would combine structured questionnaires, documentary examination and semi-structured interviews, allowing quantitative indicators to be interpreted alongside organizational explanations. Sampling should encompass federal and state agencies responsible for science, education, health, industry and environmental oversight, together with public and private higher institutions undertaking relevant research. Purposeful selection of knowledgeable officials can complement stratified institutional sampling without implying statistical representativeness where sampling frames are incomplete (Teddlie & Yu, 2007).

Questionnaires should address policy familiarity, designated responsibilities, research funding, equipment availability, workforce competence, safety arrangements and university–government collaboration. Items should use clearly defined response categories, neutral wording and pilot testing to improve interpretability across administrative and academic settings (Artino et al., 2014). Documentary evidence would include approved policies, budget allocations, committee mandates, laboratory inventories and training records. Comparing such records with respondent accounts would distinguish stated commitment from demonstrable practice (Bowen, 2009).

Geographical assessment should recognize that administrative boundaries and spatial data quality can influence apparent regional patterns. Nigerian research on mapped road crashes illustrates the importance of examining record completeness and location accuracy before interpreting geographic clustering (Alaka, Tiamiyu & Bolaji, 2021). Evidence from urban mobility surveys during movement restrictions similarly illustrates how contextual differences across Nigerian cities complicate direct comparisons unless respondents and operating conditions are defined consistently (Ajayi, Alaka & Tiamiyu, 2020). Accordingly, zone-level findings should be disaggregated by institution type, governmental tier and relevant research activity.

Qualitative interviews could explore procurement delays, regulatory ambiguity, research incentives and differences between policy expectations and operational constraints. Thematic coding would identify recurrent institutional explanations while allowing contradictory accounts to remain visible (Braun & Clarke, 2006). Locally informed interpretation is particularly important where standard survey categories may overlook institutional histories and stakeholder priorities; African methodological scholarship supports incorporating contextual knowledge into research design and interpretation (Chilisa, 2017).

Comparative analysis could report the proportions of institutions with documented nanotechnology mandates, allocated budgets, trained staff, and functional safety procedures. Missing information must remain distinguishable from verified absence. Cross-tabulations and appropriately qualified association tests could examine institutional differences, while interviews and documents explain variations that numerical summaries cannot establish independently.

Integrating the datasets through a common comparative matrix would clarify agreement, inconsistency and evidentiary gaps (Fetters, Curry & Creswell, 2013).

5. Policy Harmonization, Strategic Recommendations, and Future Directions

Policy harmonization is essential to prevent fragmented nanotechnology initiatives from producing inconsistent standards, duplicated expenditures, and uneven safeguards across Nigeria's six geopolitical zones. A coordinated framework should establish shared definitions, institutional mandates and minimum reporting requirements while allowing regional authorities and universities to respond to local research priorities. International experience indicates that technical standards and voluntary instruments can complement enforceable rules, provided their scope and implementation responsibilities are explicit (Saldívar Tanaka, 2019).

A national coordination mechanism should connect science and technology ministries, environmental and health regulators, standards bodies, research councils and higher institutions. Its functions should include maintaining an institutional registry, reviewing regulatory gaps and publishing periodic implementation assessments. Evidence from nanomedicine regulation demonstrates that mismatches between available test standards and regulatory information needs require sustained cooperation among researchers, standard-setting organizations and competent authorities (Halamoda-Kenzaoui et al., 2019).

Responsible governance also requires engagement before research priorities become fixed. Anticipation, reflection, inclusion and responsiveness offer practical criteria for evaluating funding decisions and institutional accountability (Stilgoe, Owen & Macnaghten, 2013). Risk communication must nevertheless respect local circumstances: comparative research in India and South Africa shows that nanotechnology risks acquire different institutional meanings across national settings (Beumer, 2018).

Regional investment strategies should promote shared laboratories, researcher mobility and competitive grants for institutions with demonstrable capacity-building needs. South African experience suggests that inclusive nanotechnology policy must examine who participates in research and who benefits from eventual applications, rather than treating aggregate scientific output as sufficient evidence of developmental impact (Harsh et al., 2018).

Nigeria could further prioritize technology-transfer mechanisms linking laboratory findings with public needs, especially in healthcare, environmental management and sustainable energy. Research on residential cooling efficiency illustrates the relevance of engineering optimization to energy-related innovation priorities (Sunday et al., 2019). Similarly, automated mammographic feature detection illustrates the role of computational research in medical technology development, although it does not itself establish a nanotechnology intervention (Ejofodomi et al., 2014).

Future implementation should employ staged targets covering policy adoption, laboratory safety, workforce training, joint research programmes and documented societal benefits. Regulatory review should be adaptive and proportionate to available evidence; existing legal instruments can

provide a starting point while targeted studies address uncertainty surrounding engineered nanomaterials (Resnik, 2019). Comparative monitoring should distinguish verified achievements from planned activities and report limitations transparently. Such an approach would make national coordination compatible with regional institutional differences across institutional sectors without inventing uniform readiness or guaranteed innovation outcomes.

Conclusion

This study examined the institutional conditions influencing nanotechnology policy adoption in Nigeria, with particular attention to governmental responsibilities, higher education governance, and differences across the six geopolitical zones. By integrating perspectives on regulatory development, research capacity, stakeholder awareness, and implementation barriers, the analysis established a framework for distinguishing formal policy commitments from demonstrable institutional practice.

The review identifies coordination, financing, technical infrastructure, human capital, and regulatory preparedness as central determinants of effective adoption. It also highlights the limitations of treating publication output, technological interest, or the existence of research facilities as sufficient evidence of policy implementation. Experiences from other African countries and international governance systems indicate that technological advancement requires sustained institutional leadership, transparent oversight, adaptive risk assessment, and meaningful engagement among public authorities, universities, industry, and communities. Nevertheless, available evidence does not justify definitive rankings of Nigeria's geopolitical zones or claims of verified differences in nanotechnology adoption without comparable primary data.

The proposed comparative survey framework addresses this evidentiary gap by specifying consistent indicators for policy awareness, institutional mandates, dedicated funding, workforce competence, laboratory readiness, safety procedures, and collaborative activity. Its application would enable systematic assessment of government agencies and higher institutions, supported by documentary verification and contextual interpretation. Accordingly, the contribution lies in clarifying what should be measured and how institutional variation can be evaluated, rather than reporting findings from an unimplemented survey.

Policy priorities should include establishing an interagency coordination mechanism, clarifying regulatory responsibilities, strengthening university research governance, and developing shared technical facilities accessible across regions. Dedicated training programmes, transparent financing, periodic institutional audits, and proportionate environmental and occupational safeguards are equally necessary. Future research should undertake representative fieldwork, examine differences between institutional categories, and evaluate whether policy commitments produce measurable research, safety, and developmental outcomes. Such evidence would support accountable, inclusive, and context-sensitive nanotechnology governance over successive periods.

References

1. Adeniji, I.O., Shittu, H., Opara, I.S., Elumilade, R.A. and Liadi, K.O. (2019) 'Hydrogen as a secondary energy carrier: Modeling its integration in national grids', IRE Journal, 3(1), p. 16.
2. Ajayi, O., Alaka, O.B. and Tiamiyu, R. (2020) 'Essential trip making and mode substitution during COVID-19 movement restrictions in Nigerian cities', IRE Journals, 4(4), pp. 442–465. DOI: 10.64388/IREV4I4-1722673.
3. Alaka, O.B., Ajayi, O. and Bolaji, O. (2020) 'Geospatial assessment of access to health facilities over unpaved rural road networks', International Journal of Multidisciplinary Research and Growth Evaluation, 1(5), pp. 1199–1214. DOI: 10.54660/.IJMRGE.2020.1.5.1199-1214.
4. Alaka, O.B., Tiamiyu, R. and Bolaji, O. (2021) 'Spatial clustering of road traffic crash locations on intercity corridors using national road safety records', International Journal of Multidisciplinary Research and Growth Evaluation, 2(6), pp. 1086–1101. DOI: 10.54660/.IJMRGE.2021.2.6.1086-1101.
5. Aleixandre-Tudó, J.L., Bolaños-Pizarro, M., Aleixandre, J.L. and Aleixandre-Benavent, R. (2020) 'Worldwide scientific research on nanotechnology: A bibliometric analysis of tendencies, funding, and challenges', Journal of Agricultural and Food Chemistry, 68(34), pp. 9158–9170. DOI: 10.1021/acs.jafc.0c02141.
6. Alkali, U. (2021) 'Development of university–industry interactions for knowledge-based economy in Nigeria', International Journal of Technology Management & Sustainable Development, 20(3), pp. 265–284. DOI: 10.1386/tmsd_00045_1.
7. Allan, J., Belz, S., Hoeveler, A., Hugas, M., Okuda, H., Patri, A., Rauscher, H., Silva, P., Slikker, W., Sokull-Kluettgen, B., Tong, W. and Anklam, E. (2021) 'Regulatory landscape of nanotechnology and nanoplastics from a global perspective', Regulatory Toxicology and Pharmacology, 122, Article 104885. DOI: 10.1016/j.yrtph.2021.104885.
8. Åm, H. (2011) 'Trust as glue in nanotechnology governance networks', NanoEthics, 5(1), pp. 115–128. DOI: 10.1007/s11569-011-0113-3.
9. Artino, A.R., La Rochelle, J.S., Dezee, K.J. and Gehlbach, H. (2014) 'Developing questionnaires for educational research: AMEE Guide No. 87', Medical Teacher, 36(6), pp. 463–474. DOI: 10.3109/0142159X.2014.889814.
10. Beumer, K. (2018) 'Travelling risks: How did nanotechnology become a risk in India and South Africa?', Journal of Risk Research, 21(11), pp. 1362–1383. DOI: 10.1080/13669877.2017.1304978.
11. Beumer, K. (2019) 'Nation-building and the governance of emerging technologies: The case of nanotechnology in India', NanoEthics, 13, pp. 5–19. DOI: 10.1007/s11569-018-0327-8.
12. Bolaji, O., Alaka, O.B., Ajayi, O. and Tiamiyu, R. (2019) 'Field condition assessment of roadside drainage and culvert structures on urban arterials in southwestern and north central Nigeria', IRE Journals, 3(1), pp. 663–683. DOI: 10.64388/IREV10I2-1722674.
13. Bowen, G.A. (2009) 'Document analysis as a qualitative research method', Qualitative Research Journal, 9(2), pp. 27–40. DOI: 10.3316/QRJ0902027.

14. Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology', Qualitative Research in Psychology, 3(2), pp. 77–101. DOI: 10.1191/1478088706qp063oa.
15. Capon, A., Gillespie, J., Rolfe, M. and Smith, W. (2015) 'Perceptions of risk from nanotechnologies and trust in stakeholders: A cross-sectional study of public, academic, government and business attitudes', BMC Public Health, 15, Article 424. DOI: 10.1186/s12889-015-1795-1.
16. Chilisa, B. (2017) 'Decolonising transdisciplinary research approaches: An African perspective for enhancing knowledge integration in sustainability science', Sustainability Science, 12(5), pp. 813–827. DOI: 10.1007/s11625-017-0461-1.
17. Clausen, L.P.W. and Hansen, S.F. (2018) 'The ten decrees of nanomaterials regulations', Nature Nanotechnology, 13, pp. 766–768. DOI: 10.1038/s41565-018-0256-2.
18. Corley, E.A. and Guston, D.H. (2019) 'An assessment of engaged social science research in nanoscale science and engineering communities', Science and Public Policy, 46(6), pp. 853–865. DOI: 10.1093/scipol/scz034.
19. Dutse, A.Y., Bayero, M.M., Musa, K.I. and Jibrin, M. (2021) 'University–industry linkages, enabling policies and innovative behaviours of universities in Nigeria', International Journal of Technology Management & Sustainable Development, 20(3), pp. 305–324. DOI: 10.1386/tmsd_00047_1.
20. Ejofodomi, O.A., Gideon, E.N., Oladipo, G.O. and Oshomah, E.R. (2014) 'Automated detection of architectural features in mammograms using template matching', International Journal of Biomedical Science and Engineering, 2(1), pp. 1–6.
21. Elegbede, J.A. and Lateef, A. (2019) 'Green nanotechnology in Nigeria: The research landscape, challenges and prospects', Annals of Science and Technology, 4(2), pp. 6–38. DOI: 10.2478/ast-2019-0008.
22. Enaifoghe, A., Dlamini, N.P. and Agwuna, L.U. (2020) 'African economic integration development in technological transformation: Assessing the importance of ethical leadership for policy implementation in SADC', Journal of Economics and Behavioral Studies, 12(6), pp. 11–20. DOI: 10.22610/jebs.v12i6(J).3102.
23. Etzkowitz, H. and Leydesdorff, L. (2000) 'The dynamics of innovation: From National Systems and "Mode 2" to a Triple Helix of university–industry–government relations', Research Policy, 29(2), pp. 109–123. DOI: 10.1016/S0048-7333(99)00055-4.
24. Etzkowitz, H., Webster, A., Gebhardt, C. and Terra, B.R.C. (2000) 'The future of the university and the university of the future: Evolution of ivory tower to entrepreneurial paradigm', Research Policy, 29(2), pp. 313–330. DOI: 10.1016/S0048-7333(99)00069-4.
25. Fadero, S., Oyesiji, S.O., Nwakamma, S. and Jooda, D. (2018) 'IT governance frameworks (COBIT/ITIL) and their impact on regulatory compliance in Nigerian insurance firms', IRE Journals, 2(5), pp. 478–496. DOI: 10.64388/IREV2I5-1722619.
26. Falemi, A., Akhigbe, R. and Akin-Oluyomi, O.T. (2020). A conceptual supply chain talent development model for capability building across distributed operations.

27. Fetters, M.D., Curry, L.A. and Creswell, J.W. (2013) 'Achieving integration in mixed methods designs—principles and practices', Health Services Research, 48(6pt2), pp. 2134–2156. DOI: 10.1111/1475-6773.12117.
28. Fisher, E. and Maricle, G. (2015) 'Higher-level responsiveness? Socio-technical integration within US and UK nanotechnology research priority setting', Science and Public Policy, 42(1), pp. 72–85. DOI: 10.1093/scipol/scu017.
29. Frantz, J.M., Leach, L., Pharaoh, H., Bassett, S., Roman, N.V., Smith, M.R. and Travill, A.L. (2014) 'Research capacity development in a South African higher education institution through a north-south collaboration', South African Journal of Higher Education, 28(4), pp. 1216–1229. DOI: 10.20853/28-4-396.
30. Guston, D.H. (2014) 'Understanding "anticipatory governance"', Social Studies of Science, 44(2), pp. 218–242. DOI: 10.1177/0306312713508669.
31. Halamoda-Kenzaoui, B., Holzwarth, U., Roebben, G., Bogni, A. and Bremer-Hoffmann, S. (2019) 'Mapping of the available standards against the regulatory needs for nanomedicines', WIREs Nanomedicine and Nanobiotechnology, 11(1), Article e1531. DOI: 10.1002/wnan.1531.
32. Harsh, M., Woodson, T.S., Cozzens, S., Wetmore, J.M., Soumonni, O. and Cortes, R. (2018) 'The role of emerging technologies in inclusive innovation: The case of nanotechnology in South Africa', Science and Public Policy, 45(5), pp. 597–607. DOI: 10.1093/scipol/scx079.
33. Ikwegbue, P.C., Enaifoghe, A.O., Maduku, H. and Agwuna, L.U. (2021) 'The challenges of COVID-19 pandemic and South Africa's response', African Renaissance, 18(1), p. 271.
34. Isigonis, P., Hristozov, D., Benighaus, C., Giubilato, E., Grieger, K., Pizzol, L., Semenzin, E., Linkov, I., Zabeo, A. and Marcomini, A. (2019) 'Risk governance of nanomaterials: Review of criteria and tools for risk communication, evaluation, and mitigation', Nanomaterials, 9(5), Article 696. DOI: 10.3390/nano9050696.
35. Joubert, I.A., Geppert, M., Ess, S., Nestelbacher, R., Gadermaier, G., Duschl, A., Bathke, A.C. and Himly, M. (2020) 'Public perception and knowledge on nanotechnology: A study based on a citizen science approach', NanoImpact, 17, Article 100201. DOI: 10.1016/j.impact.2019.100201.
36. Jung, H.J. and Lee, J.J. (2014) 'The impacts of science and technology policy interventions on university research: Evidence from the U.S. National Nanotechnology Initiative', Research Policy, 43(1), pp. 74–91. DOI: 10.1016/j.respol.2013.07.001.
37. Justo-Hanani, R. and Dayan, T. (2014) 'The role of the state in regulatory policy for nanomaterials risk: Analyzing the expansion of state-centric rulemaking in EU and US chemicals policies', Research Policy, 43(1), pp. 169–178. DOI: 10.1016/j.respol.2013.06.008.
38. Karkkainen, B.C. (2011) 'Does nanobiotechnology oversight present a uniquely complex challenge to interagency cooperation?', Journal of Nanoparticle Research, 13(4), pp. 1419–1425. DOI: 10.1007/s11051-011-0228-z.

39. Lateef, A., Azeez, M.A., Suaibu, O.B. and Adigun, G.O. (2021) 'A decade of nanotechnology research in Nigeria (2010–2020): A scientometric analysis', Journal of Nanoparticle Research, 23(9). DOI: 10.1007/s11051-021-05322-1.
40. Makhoba, X. and Pouris, A. (2017) 'Bibliometric analysis of the development of nanoscience research in South Africa', South African Journal of Science, 113(11/12), pp. 1–9. DOI: 10.17159/sajs.2017/20160381.
41. Malloy, T.F. (2011) 'Nanotechnology regulation: A study in claims making', ACS Nano, 5(1), pp. 5–12. DOI: 10.1021/nn103480e.
42. Musee, N., Brent, A.C. and Ashton, P.J. (2010) 'A South African research agenda to investigate the potential environmental, health and safety risks of nanotechnology', South African Journal of Science, 106(3/4), Article 159. DOI: 10.4102/sajs.v106i3/4.159.
43. Onche, V.O., Adenekan, E.T. and Sabboh, G.M. (2021) 'Influence of personal and professional attributes of secretaries on organisational success of universities in Oyo State, Nigeria', International Journal of Science Academic Research, 2(4), pp. 1355–1359.
44. Onyancha, O.B. (2021) 'Regional and international research collaboration and citation impact in selected sub-Saharan African countries in the period 2000 to 2019', Global Knowledge, Memory and Communication, 70(6/7), pp. 577–594. DOI: 10.1108/GKMC-04-2020-0039.
45. Oomen, A.G., Steinhäuser, K.G., Bleeker, E.A.J., van Broekhuizen, F., Sips, A., Dekkers, S., Wijnhoven, S.W.P. and Sayre, P.G. (2018) 'Risk assessment frameworks for nanomaterials: Scope, link to regulations, applicability, and outline for future directions in view of needed increase in efficiency', NanoImpact, 9, pp. 1–13. DOI: 10.1016/j.impact.2017.09.001.
46. Owusu, F., Kalipeni, E., Awortwi, N. and Kiiru, J.M.M. (2017) 'Building research capacity for African institutions: Confronting the research leadership gap and lessons from African research leaders', International Journal of Leadership in Education, 20(2), pp. 220–245. DOI: 10.1080/13603124.2015.1046497.
47. Rathore, A. and Mahesh, G. (2021) 'Public perception of nanotechnology: A contrast between developed and developing countries', Technology in Society, 67, Article 101751. DOI: 10.1016/j.techsoc.2021.101751.
48. Read, S.A.K., Kass, G.S., Sutcliffe, H.R. and Hankin, S.M. (2016) 'Foresight study on the risk governance of new technologies: The case of nanotechnology', Risk Analysis, 36(5), pp. 1006–1024. DOI: 10.1111/risa.12470.
49. Resnik, D.B. (2019) 'How should engineered nanomaterials be regulated for public and environmental health?', AMA Journal of Ethics, 21(4), pp. E363–E369. DOI: 10.1001/amajethics.2019.363.
50. Roco, M.C., Harthorn, B., Guston, D. and Shapira, P. (2011) 'Innovative and responsible governance of nanotechnology for societal development', Journal of Nanoparticle Research, 13, pp. 3557–3590. DOI: 10.1007/s11051-011-0454-4.
51. Russell, A.W. (2013) 'Improving legitimacy in nanotechnology policy development through stakeholder and community engagement: Forging new pathways', Review of Policy Research, 30(5), pp. 566–587. DOI: 10.1111/ropr.12037.

52. Saidi, T. and Douglas, T.S. (2017) 'Nanotechnology in South Africa – Challenges in evaluating the impact on development', South African Journal of Science, 113(7–8). DOI: 10.17159/sajs.2017/a0217.
53. Saldívar Tanaka, L. (2019) 'Regulación blanda, normas técnicas y armonización regulatoria internacional para la nanotecnología', Mundo Nano. Revista Interdisciplinaria en Nanociencias y Nanotecnología, 13(24), pp. 1e–27e. DOI: 10.22201/ceiich.24485691e.2020.24.69621.
54. Shittu, H., Shittu, M., Adeleke, O. and Adedokun, O. (2021) 'Blockchain-based energy trading models for peer-to-peer renewable microgrids', International Journal of Research in Electrical and Electronics Engineering, 4.
55. Shittu, M.A., Adeniji, I.O., Shittu, H. and Opara, I.S. (2020) 'Grounding system design optimization for medium-voltage distribution networks in emerging power markets', IRE Journal, 3, pp. 11–19.
56. Simpkin, V., Namubiru-Mwaura, E., Clarke, L. and Mossialos, E. (2019) 'Investing in health R&D: Where we are, what limits us, and how to make progress in Africa', BMJ Global Health, 4(2), Article e001047. DOI: 10.1136/bmjgh-2018-001047.
57. Singh, R.J. (2015) 'Challenges and successes of research capacity building at a rural South African university', South African Journal of Higher Education, 29(3). DOI: 10.20853/29-3-493.
58. Soeteman-Hernández, L.G., Sutcliffe, H.R., Sluijters, T., van Geuns, J., Noorlander, C.W. and Sips, A.J.A.M. (2021) 'Modernizing innovation governance to meet policy ambitions through trusted environments', NanoImpact, 21, Article 100301. DOI: 10.1016/j.impact.2021.100301.
59. Stilgoe, J., Owen, R. and Macnaghten, P. (2013) 'Developing a framework for responsible innovation', Research Policy, 42(9), pp. 1568–1580. DOI: 10.1016/j.respol.2013.05.008.
60. Stokes, E. (2013) 'Demand for command: Responding to technological risks and scientific uncertainties', Medical Law Review, 21(1), pp. 11–38. DOI: 10.1093/medlaw/fws042.
61. Sunday, E.A. and Omoegun, G.O. (2018) 'Integrating solar power solutions in small-scale manufacturing industries in Nigeria', International Journal of Scientific Research in Science, Engineering and Technology, 4(8), pp. 832–853.
62. Sunday, E.A. and Omoegun, G.O. (2019) 'Optimizing electrical load distribution for hybrid solar installations in developing economies', International Journal of Scientific Research in Mechanical and Materials Engineering, 3(6), pp. 27–47.
63. Sunday, E.A., Omoegun, G.O., Essien, M.A. and Oluokun, O.A. (2019) 'Thermodynamic efficiency and control strategies in residential air conditioning systems', International Journal of Scientific Research in Civil Engineering, 3(3), pp. 52–76.
64. Teddlie, C. and Yu, F. (2007) 'Mixed methods sampling: A typology with examples', Journal of Mixed Methods Research, 1(1), pp. 77–100. DOI: 10.1177/1558689806292430.
65. Tiamiyu, R., Alaka, O.B. and Ajayi, O. (2021) 'Emergency response coverage gaps on intercity highways in Kwara State: A network service-area analysis', International Journal of

Multidisciplinary Research and Growth Evaluation, 2(6), pp. 1102–1118. Supplied DOI: 10.54660/.IJMRGE.2021.2.6.1102-1118.

66. Twiringiyimana, R., Daniels, C. and Chataway, J. (2021) 'STI policy and governance in Sub-Saharan Africa: Fostering actors' interactions in research and innovation', Industry and Higher Education, 35(5). DOI: 10.1177/09504222211026218.
67. Whitman, J. (2007) 'The governance of nanotechnology', Science and Public Policy, 34(4), pp. 273–283. DOI: 10.3152/030234207X215551.