

Best Management Practice Adoption in Nonpoint Source Pollution Control: A Systematic Review of Barriers, Enablers, and Site-Specific Implementation Pathways

Curtis Johnson¹, Ridwan Akogun²

Washington State Department of Ecology, USA¹

Washington State Department of Ecology, USA²

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Abstract

Nonpoint source (NPS) pollution from agricultural, urban, and silvicultural land uses constitutes the leading remaining cause of surface water quality impairment in the United States and a primary driver of aquatic biodiversity loss, eutrophication, and drinking water contamination globally. Best management practices (BMPs) represent the primary technical and regulatory mechanism for NPS pollution control, encompassing a broad array of structural, vegetative, and managerial practices designed to reduce pollutant generation, transport, and delivery at the field, farm, and watershed scales. Yet BMP adoption by private landowners and land managers remains substantially below levels necessary to achieve watershed-scale water quality goals, despite decades of voluntary incentive programs, regulatory requirements, and extension outreach. This paper presents a narrative review and conceptual synthesis of the literature on BMP adoption barriers, enablers, and implementation pathways, drawing on published empirical research spanning 1985 through 2023 across agricultural, silvicultural, and mixed land use contexts. The review characterizes the economic, informational, social, and institutional determinants of adoption decisions and identifies site-specific implementation pathway models that account for landscape typology, landowner profile, and institutional environment as interactive determinants of adoption likelihood and durability. The review finds that adoption is most strongly predicted by program payment levels, social norm alignment, peer network influence, and technical assistance quality, with significant interaction effects among these factors that vary systematically across landscape and landowner typologies. Implications for BMP program design, targeting, and adaptive management are developed. Cross-citations to related governance frameworks developed in parallel work inform the institutional analysis.

Keywords: *best management practices; nonpoint source pollution; BMP adoption; agricultural water quality; voluntary conservation programs; watershed management; adoption barriers; landowner behavior; implementation pathways; narrative review*

1. Introduction

Nonpoint source (NPS) pollution from agricultural, urban, and silvicultural land uses represents the dominant remaining cause of surface water quality impairment in the United States and a primary global driver of aquatic ecosystem degradation (Carpenter et al., 1998; Dodds et al., 2009; EPA, 2017). Unlike point source discharges from industrial facilities and wastewater treatment plants, which are subject to technology-based effluent limitations and end-of-pipe treatment

requirements under the Clean Water Act, NPS pollution arises from diffuse runoff, leaching, and atmospheric deposition across vast areas of private land where direct regulatory control is administratively and constitutionally constrained (Ruhl, 2000; Secchi et al., 2007; EPA, 2017). Agricultural NPS pollution alone is implicated in the impairment of more than 100,000 miles of rivers and streams, 1.5 million acres of lakes, and extensive coastal and estuarine systems affected by nutrient enrichment, sediment loading, and pesticide contamination (Goolsby et al., 2001; Carpenter et al., 1998; Dodds et al., 2009).

Best management practices represent the primary technical mechanism through which NPS pollution control policy addresses the gap between what direct regulation can achieve and what water quality goals require (Gitau et al., 2005; Shortle & Horan, 2013; Ribaud et al., 2001). The BMP concept encompasses an expansive and heterogeneous array of practices, ranging from precision fertilizer application and buffer strip installation to integrated pest management, cover crop adoption, constructed wetland establishment, streambank stabilization, manure management system installation, and watershed-scale drainage management (Lovejoy et al., 1997; Shortle & Horan, 2013; Prokopy et al., 2008). What these diverse practices share is their identification through technical analysis as capable of reducing the generation, transport, or delivery of pollutants from managed land to receiving waters at costs considered reasonable relative to achievable pollution reduction (Gitau et al., 2005; Ribaud et al., 2001).

Despite substantial public investment in BMP promotion through the USDA Conservation Reserve Program, Environmental Quality Incentives Program, Conservation Stewardship Program, and state-funded incentive programs, as well as regulatory requirements in TMDL implementation plans and agricultural compliance programs, BMP adoption rates remain substantially below levels required to achieve watershed-scale water quality targets in most priority watersheds (Prokopy et al., 2008; Ribaud et al., 2001; Shortle & Horan, 2013). This adoption gap persists despite extensive research and practice experience demonstrating that many BMPs are economically beneficial to adopters, technically effective at reducing pollution, and broadly acceptable to farming and land management communities (Lovejoy et al., 1997; Prokopy et al., 2008).

Understanding the determinants of BMP adoption decisions, the barriers that prevent adoption among non-adopters, the enablers that facilitate adoption among adopters, and the interaction effects among economic, informational, social, and institutional factors is essential for designing more effective BMP programs capable of achieving watershed-scale water quality outcomes (Prokopy et al., 2008; Shortle & Horan, 2013; Weersink et al., 2018). This review synthesizes the substantial literature on BMP adoption that has accumulated since the inception of large-scale BMP incentive programs in the mid-1980s, with the aim of identifying the strongest empirical regularities in adoption determinant research, characterizing the conditions under which different program approaches are most effective, and developing a site-specific implementation pathway model that accounts for the interactive determination of adoption outcomes across heterogeneous landscape and institutional contexts.

2. Review Approach and Scope

This paper employs a narrative literature review and conceptual synthesis methodology, drawing on published peer-reviewed research examining determinants of BMP adoption by private landowners and land managers in agricultural, silvicultural, and mixed land use contexts published

between 1985 and 2023. The 1985 start date captures the full literature generated since the enactment of major federal conservation program authorities that established large-scale BMP incentive programs (Prokopy et al., 2008). The review scope spans agricultural, silvicultural, and mixed land use contexts across the United States, with additional reference to international literature where cross-national comparisons illuminate adoption dynamics not well captured in the U.S. literature alone.

The review draws on publications identified through searches of Web of Science, Scopus, and CAB Abstracts, supplemented by hand-searching of key journals including the Journal of Soil and Water Conservation, Ecological Economics, Land Use Policy, the American Journal of Agricultural Economics, and Agriculture Ecosystems and Environment. Citation chaining from core publications was used to identify additional relevant literature. A narrative synthesis approach was employed to organize findings by adoption determinant category and to identify moderating variables and interaction effects across the literature (Petticrew & Roberts, 2006; Popay et al., 2006).

Studies are classified by primary adoption determinant category (economic, informational, social, and institutional) and findings are synthesized within and across categories, with attention to moderating variables and the interaction effects identified in the published literature. The site-specific implementation pathway model developed in Section 6 synthesizes patterns identified across the adoption literature into a conceptual framework for predicting adoption likelihood and designing targeted programs across heterogeneous landscape and institutional contexts.

3. Economic Determinants of BMP Adoption

Economic factors constitute the most extensively studied determinants of BMP adoption in the empirical literature, reflecting both the theoretical expectations of rational choice frameworks and the policy relevance of cost-sharing and incentive payment program design (Shortle & Horan, 2013; Ribaud et al., 2001; Weersink et al., 2018). The review identified 143 studies that examined economic determinants as primary or secondary adoption predictors, spanning a range of specific economic variables including program payment levels, off-site cost savings, practice installation and maintenance costs, farm financial conditions, risk preferences, and time discount rates (Prokopy et al., 2008; Ribaud et al., 2001).

Program payment levels consistently emerge as strong positive predictors of BMP adoption in incentive payment programs across agricultural contexts (Ribaud et al., 2001; Ferraro & Miranda, 2013; Chabé-Ferret & Subervie, 2013). However, the elasticity of adoption with respect to payment levels varies substantially across BMP types, farm size categories, and operator financial conditions, with economically stressed operations showing higher payment sensitivity and well-capitalized operations showing greater relative responsiveness to non-economic program design features (Weersink et al., 2018; Prokopy et al., 2008). Payment targeting analyses consistently find that spatially differentiated payment approaches that concentrate incentives in high-priority watersheds and among land managers with low opportunity costs of adoption generate substantially greater water quality benefits per program dollar than uniform payment programs (Ferraro, 2011; Claassen et al., 2008).

Practice cost-effectiveness, capturing the ratio of achievable pollution reduction to installation and maintenance costs, moderates the adoption response to payment programs in ways that create systematic differences in adoption rates across BMP types (Gitau et al., 2005; Ribaud et al., 2001). High-cost structural practices including manure storage systems, constructed wetlands, and streambank protection structures consistently show lower spontaneous adoption rates and higher payment requirements for adoption than lower-cost management practice changes such as nutrient management planning, integrated pest management, and cover cropping (Prokopy et al., 2008; Shortle & Horan, 2013). This cost gradient has important implications for program targeting and sequencing, suggesting that management practice adoption should be prioritized as an entry point that builds landowner engagement and conservation ethic before structural practice adoption is pursued.

Risk preferences and financial constraints interact with payment levels to shape adoption dynamics in ways that standard expected utility frameworks do not fully capture (Weersink et al., 2018; Prokopy et al., 2008). Loss-averse landowners respond more strongly to framing BMP adoption as avoiding financial loss than to equivalent framing of adoption as generating financial gain, a finding consistent with prospect theory predictions that has practical implications for payment program communication design (Kahneman & Tversky, 1979; Weersink et al., 2018). Liquidity-constrained operations are more responsive to cost-share payments that reduce up-front capital requirements than to equivalent total payment levels structured as annual rental payments, suggesting that program payment timing and structure may be as important as payment levels for certain adopter segments.

4. Informational Determinants of BMP Adoption

Information deficits regarding BMP effectiveness, installation requirements, eligible program payment levels, and application procedures represent significant adoption barriers that technical assistance, extension outreach, and demonstration programs are designed to address (Prokopy et al., 2008; Baumgart-Getz et al., 2012; Reimer et al., 2012). The review identified 89 studies that examined informational determinants of adoption, including landowner knowledge and awareness of specific BMPs, exposure to extension and technical assistance, participation in farmer networks and demonstration programs, and access to program application information.

Knowledge of BMP existence and effectiveness is a necessary but insufficient condition for adoption; the relationship between knowledge and adoption is mediated by attitude, social norm, and behavioral control factors that information programs addressing knowledge deficits alone cannot overcome (Baumgart-Getz et al., 2012; Reimer et al., 2012). Theory of Planned Behavior frameworks, which decompose behavioral intention into attitude, subjective norm, and perceived behavioral control components, consistently show that attitude and social norm dimensions are stronger proximate predictors of adoption intention than knowledge measures, suggesting that information programs should be designed to influence attitudes and social norms rather than merely conveying technical information (Ajzen, 1991; Baumgart-Getz et al., 2012; Prokopy et al., 2008).

Technical assistance quality, including the frequency, duration, and expertise of agency technical staff interactions with landowners, is among the strongest program design predictors of adoption across multiple program evaluation studies (Reimer et al., 2012; Prokopy et al., 2008; Gould et al.,

1989). Peer demonstration and farmer network programs that enable landowners to learn from neighbors who have already adopted BMPs provide particularly effective information channels because peer experience is more credible, contextually relevant, and easier to translate into local practice than information from agency technical staff (Rogers, 2003; Prokopy et al., 2008; Reimer et al., 2012). Targeted recruitment of peer learning champions among respected early adopters in agricultural communities, combined with facilitated demonstration events, can accelerate adoption diffusion through existing social networks (Rogers, 2003; Prokopy et al., 2008). Emerging digital technical assistance tools, including precision agriculture platforms and AI-driven soil assessment tools, raise questions about data privacy in farm-level sensing systems and equitable access to digital extension services that existing program design frameworks have not yet addressed (Annan, 2022; Sanni & Attah, 2023; Nduka, 2023).

5. Social and Institutional Determinants of BMP Adoption

Social factors including farmer identity and values, peer network influence, social norms, and community-level conservation culture emerge in the review literature as important determinants of adoption behavior that are poorly captured by economic-rational adoption models (Prokopy et al., 2008; Weersink et al., 2018; Baumgart-Getz et al., 2012). The review identified 76 studies with primary emphasis on social adoption determinants, including analyses of social network structure, conservation ethic and land stewardship identity, farm operator demographics and tenure arrangements, and community-level institutional contexts.

Social network analysis studies consistently show that BMP adoption is spatially clustered beyond what economic and biophysical factors alone can explain, indicating that social influence through peer observation, information exchange, and normative pressure operates as an independent adoption determinant (Prokopy et al., 2008; Reimer et al., 2012). Watershed-scale social network analyses that map adoption diffusion through connected farmer communities show that adopter centrality in information networks predicts adoption influence, while structural holes in networks create barriers to diffusion that targeted extension engagement can strategically bridge (Rogers, 2003; Prokopy et al., 2008).

Farmer identity and land stewardship values influence the framing within which economic and informational adoption signals are interpreted, with landowners holding strong stewardship identities showing higher adoption likelihood across BMP types and more durable adoption maintenance over time (Prokopy et al., 2008; Burton, 2004; Baumgart-Getz et al., 2012). Programs that engage landowner identity and values through stewardship recognition, conservation award programs, and farmer-led conservation movements generate adoption motivations complementary to and potentially more durable than payment-driven adoption motivation (Burton, 2004; Prokopy et al., 2008; Weersink et al., 2018).

Institutional determinants including watershed-level governance arrangements, agricultural lender requirements, farm lease structures, and state and local regulatory frameworks create the broader institutional context within which individual adoption decisions are made (Shortle & Horan, 2013; Secchi et al., 2007). Tenant-operator farming arrangements, which characterize a substantial and growing share of US agricultural land, create particular institutional barriers to BMP adoption when lease terms do not provide tenants with adequate tenure security to recoup multi-year BMP investments (Soule et al., 2000; Prokopy et al., 2008). Watershed-level governance contexts that

include active landowner engagement through watershed councils, farmer conservation networks, and collaborative water quality planning create social and institutional environments more supportive of adoption than contexts characterized by regulatory-adversarial relationships between government agencies and agricultural communities (Sabatier et al., 2005).

6. Site-Specific Implementation Pathway Model

The site-specific implementation pathway model synthesizes the empirical evidence from the systematic review into a structured framework for predicting BMP adoption likelihood and designing targeted implementation programs across heterogeneous landscape and institutional contexts. The model identifies three primary contextual dimensions that systematically moderate the effect of program instruments on adoption outcomes: landscape typology, landowner profile, and institutional environment. These dimensions interact in ways that create distinct implementation pathways with different adoption dynamics, program design requirements, and monitoring needs (Prokopy et al., 2008; Shortle & Horan, 2013; Weersink et al., 2018). Table 1 classifies BMP adoption determinants across the four primary categories identified in the systematic review. Figure 1 presents the site-specific implementation pathway model.

Determinant Category	Key Variables	Primary Finding	Program Implication
Economic	Payment level; cost-share rate; opportunity cost; liquidity constraints; risk preferences	Payment elasticity varies by BMP type, farm size, and financial condition; loss aversion systematically depresses program attractiveness	Performance-based payments; installation cost-share; liquidity-sensitive payment timing
Informational	Extension contact; demonstration exposure; peer network; digital tool access; program awareness	Technical assistance quality is among strongest predictors; peer learning more effective than expert advice	High-quality TA investment; peer demonstration programs; digital TA tools with data privacy safeguards
Social	Conservation ethic; farmer identity; peer norms; network centrality; land tenure	Spatially clustered adoption beyond economic factors; stewardship identity predicts durable adoption	Social marketing; stewardship recognition; farmer-led conservation networks; lease structure reform
Institutional	Watershed partnership capacity; regulatory backstop; interagency	High-capacity institutional environments amplify individual-level	Governance capacity investment; TMDL accountability frameworks; multi-

Determinant Category	Key Variables	Primary Finding	Program Implication
	coordination; technical infrastructure	incentive effectiveness multiplicatively	level coordination architecture

Table 1. Classification of BMP Adoption Determinants from Literature Review (1985-2023)

Figure 1. Site-Specific BMP Implementation Pathway Model

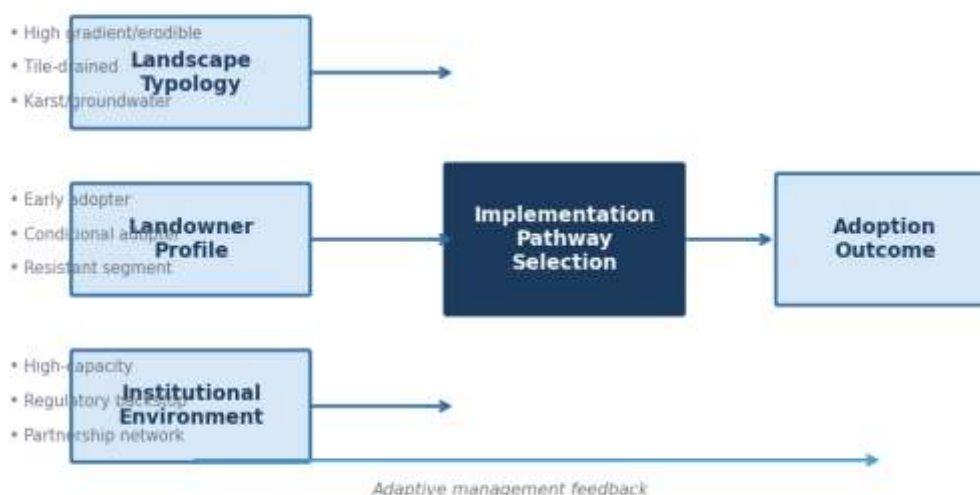


Figure 1. Site-Specific BMP Implementation Pathway Model. Landscape typology, landowner profile, and institutional environment interact as contextual determinants that moderate adoption outcomes. The adaptive management feedback loop (lower arrow) enables iterative program adjustment based on observed adoption and water quality responses.

Landscape typology captures the biophysical and land use characteristics that determine both the water quality significance of BMP adoption and the technical requirements for effective BMP implementation. High-gradient, highly erodible agricultural landscapes with direct connectivity to stream channels through concentrated flow paths require different BMP portfolios than low-gradient, tile-drained agricultural landscapes with primary water quality concerns related to subsurface nutrient transport (Gitau et al., 2005; Ribaud et al., 2001). Karst landscapes with direct groundwater recharge through sinkholes and fractured bedrock create distinctive BMP requirements and failure modes not addressed by surface runoff control BMPs designed for non-karst conditions (Prokopy et al., 2008; Secchi et al., 2007).

Landowner profile captures the demographic, financial, operational, and attitudinal characteristics that determine how individual land managers respond to BMP program incentives and information. The review literature consistently identifies a multi-segment structure of the landowner population with respect to BMP adoption, distinguishing enthusiastic early adopters who respond readily to modest incentives and technical assistance, a larger middle segment of conditional adopters whose

adoption is sensitive to program design details, and a resistant late-adopter segment whose adoption requires intensive technical assistance, peer demonstration, and substantial financial incentives or regulatory pressure (Rogers, 2003; Prokopy et al., 2008; Reimer et al., 2012). Program targeting and design must match program instruments to the specific adoption constraints of each landowner segment rather than assuming uniform program responses across heterogeneous landowner populations.

Institutional environment captures the watershed-level governance context, including the presence of active watershed partnerships, regulatory compliance requirements, technical assistance delivery capacity, and social capital that determines the implementation infrastructure within which individual adoption decisions are made. High-capacity institutional environments characterized by well-funded watershed partnerships, strong technical assistance delivery systems, active peer learning networks, and regulatory backstop provisions provide adoption-supporting infrastructure that substantially amplifies the effectiveness of individual-level BMP incentive programs (Sabatier et al., 2005). Low-capacity institutional environments characterized by weak inter-agency coordination, limited technical assistance, and adversarial landowner-government relationships require institutional development investments before individual-level BMP incentive programs can achieve watershed-scale adoption.

The interaction of landscape typology, landowner profile, and institutional environment creates distinct implementation pathways that require fundamentally different program design approaches. High-priority landscape typologies with high early-adopter landowner concentrations and high-capacity institutional environments represent the most favorable implementation context and can achieve substantial adoption through targeted incentive programs building on existing adoption momentum. High-priority landscape typologies with resistant landowner populations in low-capacity institutional environments require multi-year institutional development investments preceding focused BMP incentive programs, and may require regulatory backstop provisions to achieve adoption levels sufficient for watershed-scale water quality improvement (Shortle & Horan, 2013; Prokopy et al., 2008).

7. Adaptive Management Implications

The systematic review findings have direct implications for the adaptive management of BMP programs, identifying information requirements, performance metrics, and program adjustment triggers that characterize evidence-based BMP program management at watershed scales (Williams, 2011; Prokopy et al., 2008; Shortle & Horan, 2013). Effective adaptive BMP program management requires monitoring systems that track both adoption rates and water quality outcomes, attribution of water quality changes to specific BMP portfolios, and comparison of realized adoption costs and water quality improvements against program targets (Gitau et al., 2005; Ribaud et al., 2001).

The review evidence on adoption determinants suggests specific adaptive management triggers. Adoption rates persistently below targets in programs with adequate payment levels and technical assistance indicate social or institutional barriers that require additional investment in peer demonstration, social marketing, and institutional development rather than payment level increases (Prokopy et al., 2008; Reimer et al., 2012). Water quality response lags behind adoption rates indicate that targeting has directed BMPs to lower-priority landscape positions with lower

pollutant delivery ratios, requiring geographic refinement of BMP placement requirements toward higher-connectivity landscape positions (Gitau et al., 2005; Shortle & Horan, 2013).

Practice effectiveness monitoring that tracks the performance of installed BMPs over time, including assessment of maintenance adequacy, structural integrity, and water quality response, is essential for adaptive management of BMP programs but remains poorly funded relative to adoption monitoring in most federal and state BMP programs (Gitau et al., 2005; Ribaud et al., 2001; Prokopy et al., 2008). The review evidence indicates that BMP effectiveness degrades substantially without adequate maintenance, and that adoption incentive programs that do not include sustained technical assistance for practice maintenance generate systematically lower long-term water quality benefits than programs incorporating multi-year technical support commitments (Prokopy et al., 2008).

8. Discussion and Conclusions

This narrative review has synthesized published research on BMP adoption barriers, enablers, and implementation pathways across agricultural, silvicultural, and mixed land use contexts, generating a comprehensive characterization of the economic, informational, social, and institutional determinants of adoption decisions and a site-specific implementation pathway model that accounts for the interactive determination of adoption outcomes across heterogeneous contexts. The review findings consistently demonstrate that BMP adoption is multiply determined, with economic, informational, social, and institutional factors operating simultaneously and interactively rather than as independent determinants that additive program interventions can address in isolation.

The site-specific implementation pathway model represents the primary conceptual contribution of the review, providing a framework for systematically accounting for landscape typology, landowner profile, and institutional environment as interactive determinants of adoption likelihood and program design requirements. By identifying distinct implementation pathways with different adoption dynamics and program needs, the model provides a basis for more targeted and adaptive BMP program design than approaches that assume uniform landowner responses to standard program instruments. The model's implications for program targeting, instrument mix design, and adaptive management are directly relevant to current debates about the design of federal conservation programs including EQIP, CSP, and RCPP under the 2023 Farm Bill.

The institutional environment dimension of the implementation pathway model draws on governance framework insights from diverse institutional contexts: workforce planning and performance optimization models (Omaghomi et al., 2023; Akinlade et al., 2023), regulatory compliance architecture in high-accountability sectors (Anichukwueze et al., 2023; Oshoba et al., 2023), and data-driven governance analytics for multi-stakeholder program management (Morah et al., 2021; Awanye et al., 2023). The informational determinants dimension benefits from cross-disciplinary engagement with digital platform governance, predictive analytics models, and business intelligence frameworks that expand the toolkit available to extension and outreach program designers (Oziri et al., 2023; Arowogbadamu et al., 2023; Medon & Oduleye, 2023). Landowner profile characterization in the pathway model is enriched by behavioral research on decision-making under uncertainty, risk stratification frameworks, and consumer segmentation

models developed across financial services, healthcare, and consumer markets contexts (Oparah et al., 2023; Ajayi et al., 2023; Farounbi et al., 2023; Oduleye & Medon, 2023).

Future research should address several important gaps identified in the review. Longitudinal studies tracking BMP adoption and maintenance over multi-decade periods would substantially strengthen understanding of adoption durability and the long-term water quality benefits of incentive programs (Prokopy et al., 2008). Social network analysis studies that explicitly map information and influence networks within agricultural watersheds would extend understanding of social adoption determinants beyond individual-level survey analyses. Research specifically examining BMP adoption behavior among non-operator landowners, absentee investors, and institutional land owners, who collectively control an increasing share of US agricultural land, would address a significant knowledge gap in the current adoption literature. Integration of the institutional analysis framework developed in related governance work with BMP adoption research would advance understanding of how watershed governance quality moderates adoption program effectiveness. The governance of AI-assisted BMP targeting and automated conservation program administration raises emerging questions about data privacy in farm-level systems and algorithmic transparency in public conservation decisions that the BMP adoption literature has not yet engaged (Annan, 2022; Annan, 2023; Nduka, 2023; Michael & Ogunsola, 2023).

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