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# Cover Story

For decades, Malaysia's palm oil industry has lifted rural economies, powered export revenues, and positioned the nation as a global agricultural powerhouse. That fortune is showing signs of fatigue. The industry has reached a state of stagnation. Yields are flat. The land area has reached its limit. Labour is scarce, and trees are ageing. Industry leaders warn of a "full-blown Code Blue" crisis. To secure the next chapter of growth, we must fundamentally change our mindset, from just exploiting 20% of the oil palm—the oil itself. The future lies in the other 80%. It lies in the empty fruit bunches, fronds, trunks, and palm oil mill effluent, now treated as waste. Currently, our national productivity is being dragged down by a crisis of ageing trees and a low replanting rate. We risk entrenching inefficiency and losing billions in potential revenue. We need a national "rush to replant," supported by innovative financing mechanisms. As we replant, we must redesign estates to accomodate mechanisation and automation that will break our dependence on foreign labour.

The real game-changer lies downstream. For every tonne of palm oil produced, we leave behind four tonnes of biomass. Today, it represents a multi-billion-ringgit economic frontier. We have pilot plants that can turn empty fruit bunches into charcoal, graphite, bio-fertiliser, and high-density fibreboard. What we need now is the commercial will to scale. Ageing trunks from replanted areas must be processed for bio-based materials or next-generation biofuels. Empty bunches are converted into value-added products for the chemical and manufacturing industries. This is the circular bio-economy in action. This transition from a single-commodity model to a multi-feedstock bio-refinery model does more than just create new revenue streams. It solves our biggest existential threats.

It enhances sustainability. It stabilises prices. It revitalizes rural economies: A biomass industry creates high-tech jobs in manufacturing, logistics, and research. To navigate this transition, we need a war cabinet mentality. First, we must supercharge R&D commercialisation. We need adequate fund to bridge the "valley of death" between laboratory prototypes and commercially viable, investor-ready technologies. It should focus on scaling up the conversion of biomass into high-value products, not just low-margin alternatives. Second, we need to create a market for biomass products. This requires policy intervention. Mandates for sustainable aviation fuel, green procurement policies for bio-based materials in government projects, and incentives for using bio-fertilisers can jumpstart demand.

We must rebrand the industry. We are no longer just a commodity producer. We are a leader in the circular bio-economy. The narrative must shift from cheap cooking oil to sustainable innovation and high-tech manufacturing. We need to attract the brightest minds—engineers, biotechnologists, and chemists—to an industry that offers a future, not just a job. The golden goose of the 20th century was the oil. The goose of the 21st century will be the entire palm. The pradigm must change.

(Academician Professor Dato' Dr Ahmad Ibrahim, UCSI University, Malaysia)

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# About the Journal

Agricultural & Rural Studies (**A&R**, **ISSN 2959-9784**) is an exclusively digital, open-access journal dedicated to advancing interdisciplinary scholarship at the critical nexus of agricultural sustainability, rural revitalization, and farmer well-being. Published quarterly, **A&R** features a range of content types—including original research, reviews, perspectives, and commentaries—serving as a professional and innovative platform for rigorous academic dialogue and global knowledge dissemination.

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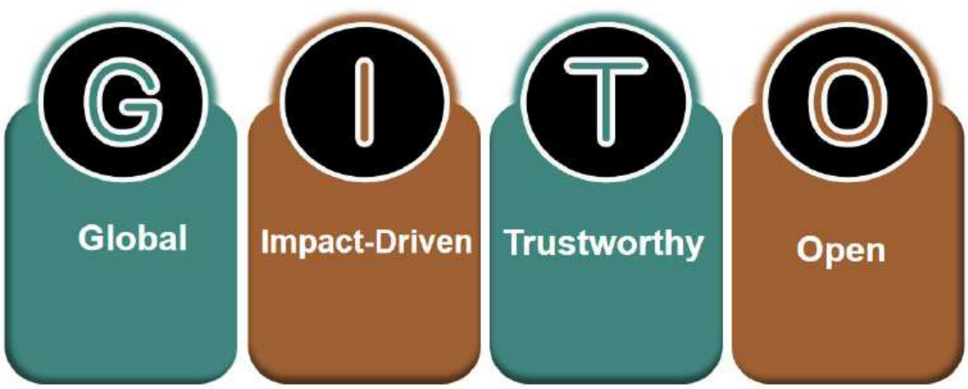

Agricultural & Rural Studies

*Review*

# Repositioning the Palm Oil Industry from Oil Extraction to Whole Palm Valorization

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**Abstract:** The palm oil industry is a major contributor to agricultural production, rural livelihoods, and industrial development in many tropical economies. However, its long-term competitiveness is increasingly constrainted by stagnant yields, ageing plantations, labor shortages, slow replanting, and rising environmental expectations. Although previous studies have examined palm biomass utilization, waste management, renewable energy and low-carbon technologies, these topics are often treated as separate technical domains rather than as connected components of an integrated industry transition. This review addresses that gap by advancing a whole palm valorization perspective, defined here as the coordinated recovery, conversion, and value creation of plantation and mill-generated biomass and residual streams. For conceptual clarity, the core analytical boundary is restricted to resources generated directly within the plantation-mill system, while downstream post-consumer streams such as used cooking oil are treated only as related circular-bioeconomy boundary cases. The review compares major valorization pathways in term of technical maturity, economic feasibility, environmental benefits, logistical constraints, and implementation potential. Evidence from the literature shows that large fractions of fresh fruit bunches become residual resources. Besides, palm oil mill effluent (POME) and mill biomass offer measurable opportunities for energy recovery, emissions reduction, nutrient recycling, and downstream value creation. Nevertheless, implementation remains uneven due to feedstock logistics, capital requirements, market uncertainty, limited offtake arrangements, and fragmented governance. Overall, this review provides an integrated and evidence-based foundation for repositioning the palm oil industry beyond oil extraction toward a circular, lower-carbon, and more resource-efficient development pathway.

**Keywords:** palm oil industry; whole palm valorization; circular bioeconomy; biomass utilization; Sustainable Development Goals (SDGs)

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## 1. Introduction

Oil palm has emerged as one of the most productive and strategically important plantation crops in the tropical agricultural economy (Naidu & Moorthy, 2021; Putri et al., 2022). Its high oil yield, wide industrial use, and strong global demand have made palm oil a major commodity in food, oleochemicals, cosmetics, and energy-related sectors contributions have given palm oil a central place in agricultural development and industrial growth (Zhang et al., 2025).

However, the operating context of the industry is changing. Productivity growth has slowed in many areas, and sustainability expectations have become more demanding (Naidu & Moorthy, 2021). At the same time, public and scientific attention has expanded beyond oil yield alone. Greater attention is now placed on waste management, resource efficiency, emissions performance (Wahyudin & Oge, 2025), and the overall structure of palm-based production systems (Awoh et al., 2023). This shift suggests that the long-term future of the industry cannot be assessed only through the quantity of oil produced.

Previous studies have provided useful insights into oil palm biomass utilization, palm oil mill effluent (POME) management (Kurniawan et al., 2025), renewable energy generation (Wu et al., 2017), bio-based materials and low-carbon technologies (Manikandan et al., 2026). However, these themes are commonly reviewed as separate technological or environmental topics. This creates an important research gap: there is still limited synthesis explaining how plantation residues, mill by-products, liquid effluent, downstream product development, and carbon-linked opportunities interact as part of a single plantation-mill resource system. As a result, the existing literature has not sufficiently clarified how these separated pathways can collectively reposition the palm oil industry from a narrow oil-extraction model toward whole palm valorization.

This review addresses that gap by adopting whole palm valorization as the central analytical lens. The contribution of this review is not simply to list additional uses for oil palm residues, but to integrate scattered evidence into a sector-level framework for understanding the palm oil industry as a multi-output bioresource system. The novelty of the review lies in three related contributions: first, it defines the plantation-mill boundary of whole palm valorization and distinguishes production-based residual resources from broader downstream circular-economy streams such as used cooking oil; second, it compares major valorization pathways according to maturity, feasibility, environmental benefit, logistics constraints, and implementation potential; and third, it links technical pathways with governance, commercialization, carbon-value creation, and stakeholder participations. By doing so, this review shows how field residues, mill residues, POME, energy recovery, nutrient recycling, carbon reduction, and downstream product development can be analyzed together rather than as isolated themes. The main objective is therefore to examine how whole palm valorization can advance the palm oil industry beyond oil extraction while supporting diversified income, circular bioeconomy practices, and lower-emission production. This objective aligns with the UN SDGs, particularly SDG1 (No poverty), SDG2 (Zero hunger) and SDG 13 (Climate Action), particularly through resource efficiency, waste reduction, greenhouse gas mitigation, and circular value creation.

*Literature Search and Selection Approach*

This review was developed as a narrative and integrative literature review. Relevant literature was identified through Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar using combinations of search terms including "oil palm," "palm oil industry," "oil palm biomass," "empty fruit bunch," "oil palm frond," "oil palm trunk," "palm kernel shell," "mesocarp fibre," "palm oil mill effluent," "biogas," "biomass valorization," "biorefinery," "circular bioeconomy," "carbon credit," "sustainable palm oil," and "smallholder." The literature surveyed covered publications from 2008 to 2026, with stronger emphasis on studies published from 2021 onwards because of their relevance to recent circular bioeconomy, low-carbon, and governance discussions. Sources were included when they addressed plantation residues, milling by-products, POME treatment, valorization technologies, techno-economic or environmental performance, policy, or stakeholder implementation in the oil palm sector. Sources were excluded when they focused on unrelated edible-oil markets, non-oil-palm biomass, downstream post-consumer wastes without a clear palm-based link, or topics outside the plantation-mill boundary defined in this review. As the reviewed studies used heterogenous methods, units, and system boundaries, the evidence was synthesized thematically and comparatively rather than through a formal meta-analysis. This plantation-mill boundary was applied consistently to prevent production-based whole palm valorization from being conflated with downstream post-consumer circular-economy stream.

## 2. Rationale for Repositioning the Palm Oil Industry Beyond Oil Extraction

For a long time, the palm oil industry has been organized through the extraction and sale of crude palm oil and palm kernel oil (Rajakal et al., 2024). This oil-centred structure generated substantial economic returns because these two products remain the main commercial outputs of the crop (Rajakal et al., 2024). However, the conditions that supported this model are changing. Land expansion is increasingly constrained, labor availability is uncertain, and markets are placing stronger emphasis on sustainability, traceability, and resource efficiency (Cheah et al., 2023; Murphy et al., 2021). Under these conditions, reliance on oil alone is unlikely to provide a sufficient foundation for long-term competitiveness.

The need to reposition the industry reflects a broader change in how value is understood in agricultural and bio-based sectors. In the past, value was measured mainly through primary commodity output. Today, value is also linked to resource efficiency, by-product valorization, emissions performance, downstream diversification, and circular production (Figure 1). This change is particularly relevant to oil palm because the crop generates large quantities of biomass and residual resources in addition to oil. Therefore, broadening value assessment should be understood as expanding the industry's development pathway rather than replacing the central role of crude palm oil and palm kernel oil (Cheah et al., 2023; Kurniawan et al., 2025).

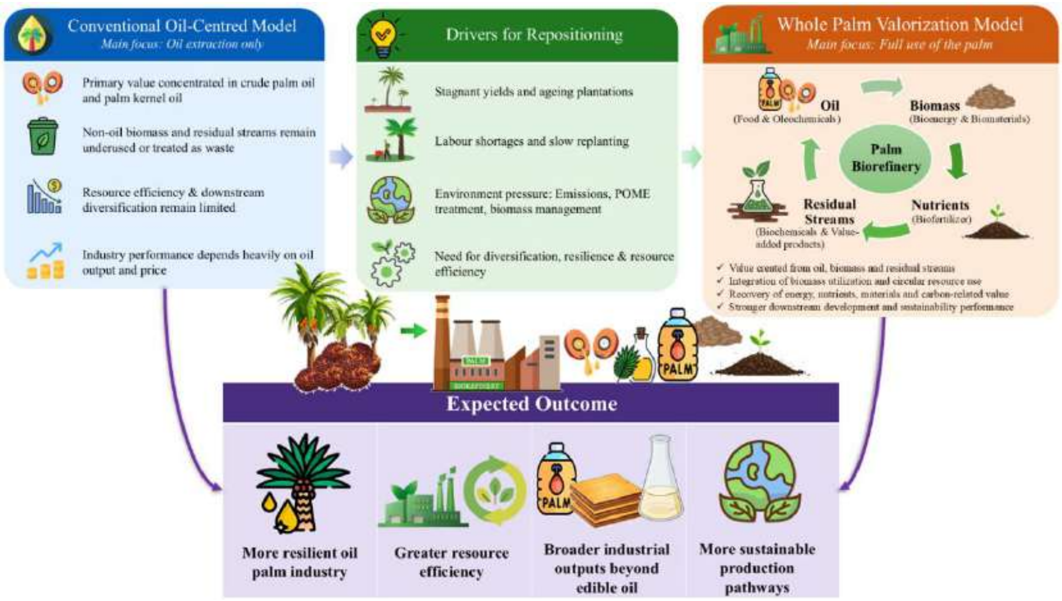


**Figure 1.** Conceptual Framework for Repositioning the Oil Palm Industry from Oil Extraction to Whole Palm Valorization.

Collectively, this expanded understanding of value provides the basis for repositioning the sector. Repositioning the industry beyond oil extraction does not reduce the importance of oil; rather, it shows why oil output must be interpreted alongside the wider resource base generated by the same production system. This review does not attempt a complete sector-wide techno-economic quantification as a remaining research need. Instead, it synthesizes available quantitative evidence where comparable data are reported in the literature and identifies more complete pathway-level quantification as a remaining research need. The key issue is that conventional performance indicators based mainly on crude palm oil and palm kernel oil do not fully capture the wider value, cost, and risk associated with the plantation-mill resource base (W. Ng et al., 2025). A broader resource perspective can therefore help the industry reduce dependence on a single dominant product, improve resource efficiency, and identify additional value from residues that are already generated within the system.

This repositioning is important for both industrial competitiveness and sustainability performance. Global manufacturing, energy, and agricultural systems are moving toward renewable feedstocks, circular production, and lower-emission pathways. If the palm oil industry shifts from a narrow oil-extraction model toward a wider resource-based model, it can better respond to these transitions while retaining its strategic role in tropical economies (Cheah et al., 2023; Murphy et al., 2021).

*Structural Constraints in the Conventional Oil-Centered Palm Oil Model*

The conventional oil-centered palm oil model faces several structural constraints (Table 1). One major constraint is stagnant yield performance. In Malaysia, the national crude palm oil yield was reported at about 3.28 tonnes $ha^{-1}$ in 2024. Industry discussions have suggested that a more realistic medium-term target is approximately 4.5 tonnes $ha^{-1}$ rather than the often cited 6–7 tonnes $ha^{-1}$ target (Asia Palm Oil Magazine, 2026). This gap shows that yield improvement remains central to competitiveness. Historical production patterns also indicate that output growth has not always kept pace with area expansion. For example, Malaysian oil palm planted area increased from 4.85 million ha in 2010 to 5.74 million ha in 2021, while crude palm oil production rose from 16.99 million tonnes to 18.12 million tones over the same period (Ahmad et al., 2024). These figures suggest that the yield challenge is not solely technological, but also reflects replanting delays, plantation age structure, labor availability, management capacity, and environmental variability (Murphy et al., 2021).

**Table 1.** Major structural constraints that limit the performance and long-term resilience of the conventional oil-centered palm oil model.

| Constraint | Description | Implication for the industry | References |
|---|---|---|---|
| Stagnant yields | CPO yield around 3.28 tonnes ha$^{-1}$ (2024), 3.50 tonnes ha$^{-1}$ (2025); still below the proposed 4.5 tonnes ha$^{-1}$ (2035) | Reduces productivity and competitiveness | (Asia Palm Oil Magazine, 2026; Malaysian Palm Oil Board, 2026) |
| Ageing plantations | Older palms reduce output; delayed replanting extends low-yield cycles | Weakens output and increases replanting urgency | (Khor et al., 2023) |
| Slow replanting | High replanting cost and temporary income loss | Prolongs low productivity cycles | (J. Ng, 2025) |
| Labor dependence | Harvesting and field management remain labor-intensive | Increases vulnerability to labor shortages and rising costs | (Haryati et al., 2022; Zapata-Hernández et al., 2024) |
| Environmental pressure | Emissions, POME treatment, biomass management, and resource efficiency concerns | Increases regulatory, market, reputational, and pollution-management pressure | (Chia et al., 2024; Kurniawan et al., 2025) |

Note: CPO refer to Crude Palm Oil; tonnes ha$^{-1}$ refer to tonnes per hectare.

Aging plantations create another constraint. Older palms produce less and are more difficult to manage and harvest (Khor et al., 2023). Replanting can solve this problem, but many growers delay replanting because it requires high investment and leads to temporary income loss (J. Ng, 2025). This issue is more serious for smallholders because they have fewer financial resources and less flexibility during the replanting period (Touch et al., 2024).

Labor dependence remains a serious limitation. The industry relies heavily on manual work for harvesting, pruning, collection, and field maintenance. Labor shortages, rising labor costs, and changes in labor policy create major operational concerns (Zapata-Hernández et al., 2024). Mechanization is a possible solution, but its adoption is uneven and is often limited by terrain, estate design, and access to capital (Haryati et al., 2022).

Environmental pressure creates another constraint. Current concerns include emissions, waste generation, effluent management, and overall resource efficiency. These concerns influence public perception, regulatory attention, and market expectations (Naidu & Moorthy, 2021). The conventional focus on oil extraction alone does not reflect the full range of issues shaping the industry.

Taken together, these constraints show that the traditional oil-centered model is under increasing pressure. The issue is not only that oil production faces productivity, labor, and environmental challenges. The deeper issue is that the current production model captures only a fraction of the crop's total value, while many co-products and residual streams remain underutilized.

## 3. Whole Palm Valorization: Concept, Scope and Analytical Boundary

Building on the repositioning rationale above, whole palm valorization is defined in this review as an integrated development approach that seeks to maximize useful value from the oil palm crop and its production residues through coordinated recovery, conversion, reuse, and upgrading of plantation and milling streams. Importantly, the concept is used here as an analytical boundary and strategic framework, not simply as another term for biomass utilization. It interprets the oil palm production system as a multi-output bioresource platform in which crude palm oil, palm kernel oil, lignocellulosic biomass, solid mill residues, liquid effluent, nutrients, energy, and carbon-related value are considered together. This definition makes whole palm valorization an analytical boundary and strategic framework, rather than a synonym for general biomass utilization (Rendón-Camargo et al., 2026). For analytical consistency, this review applies three boundary criteria. First, the resource must be generated directly during oil palm cultivation, replanting, harvesting, or crude palm oil milling. Second, the resource must be recoverable or manageable within the plantation-mill production chain before the consumer-use stage. Third, its valorization must contribute to resource efficiency, downstream product development, nutrient recovery, renewable energy generation, emissions reduction, or carbon-linked value creation. These criteria define the scope of the review and prevent the concept from becoming too broad.

The core analytical boundary therefore includes field-generated resources such as fronds and trunks, mill generated solid residues such as empty fruit bunches (EFB), mesocarp fibre (MF), palm kernel shells, and other fibre-rich fractions; liquid residues such as POME; and treatment-derived streams such as sludge, digestate, recovered nutrients, biogas, heat, electricity, biochar, biomaterials, or carbon products derived from these plantation and mill resources. These streams are included because plantation managers, mill operators, logistics providers, and downstream processors can directly influence their recovery, handling, conversion, and value creation (Nasir et al., 2018; Wu et al., 2017).

By contrast, downstream and post-consumer waste streams, including used cooking oil, are excluded from the core analytical boundary of whole palm valorization in this review. Although these streams are relevant to the wider palm-based circular bioeconomy because they extend the useful life of palm-derived materials after consumption, they are not generated directly by plantation or milling operations. Used cooking oil is therefore treated as a boundary case that helps distinguish whole palm valorization from broader circular economy opportunities, rather than as a core valorization pathway (Wahyudin & Oge, 2025).

The relationship between whole palm valorization and related concepts is therefore complementary but not interchangeable. Biomass utilization refers to the use of individual feedstocks such as empty fruit bunches, fronds, trunks, shells, fibres, or POME. Biorefinery development refers to the conversion platforms that transform these feedstocks into fuels, chemicals, materials, energy, or other products. Circular bioeconomy provides the wider sustainability logic of keeping renewable biological resources, nutrients, and energy in productive use for as long as possible. Carbon value creation focuses on climate-linked value, including methane capture, emissions avoidance, biochar, carbon products, or carbon finance. Whole palm valorization integrates these narrower concepts into a sector-level framework that asks how the plantation-mill resource base can be organized, compared, commercialized, and governed as a coherent development pathway (Rajakal et al., 2024).

In this way, whole palm valorization differs from the conventional oil-centred model. In the oil-centred model, value is concentrated mainly in crude palm oil and palm kernel oil, while other outputs are treated as secondary residues. In the whole palm valorization model, oil remains important, but the associated biomass, effluent, nutrients, energy potential, and carbon-linked opportunities are also treated as strategic resources. This shift changes how industry performance is assessed because it connects productivity, waste reduction, downstream diversification, emissions performance, and governance within one internally consistent framework.

## 4. Valorization Pathways of Oil Palm Biomass and Residual Resources

Within the defined plantation-mill boundary, the oil palm production system generates a wide range of biomass and residual resources from both plantation and milling activities. These resources include field residues, solid processing by-products, and liquid effluent streams (Terry et al., 2021). Their scale is substantial (Kurniawan et al., 2025). In a typical palm oil mill system, only about one-fifth of processed fresh fruit bunches become crude palm oil, while the remaining fraction appears as solid residues and liquid effluent; one estimate reports that crude palm oil represents about 21% of fresh fruit bunches, with the remaining 79% becoming biomass residues and waste stream (Chew et al., 2024). Another industry-based study reported that almost 70% of fresh fruit bunches can be converted into empty fruit bunches, mesocarp fiber, palm kernel shell, and liquid effluent after milling (Ahmad et al., 2024). These quantities show why whole palm valorization should be treated as an industrial resource strategy rather than only a waste-management response. A whole palm valorization approach views these materials differently. It treats oil palm biomass and residual resources as renewable feedstocks that can support new value chains in energy, materials, agriculture, and environmental management (Zhang et al., 2025). The analytical significance of this shift lies not only in waste reduction, but also in creating additional economic outputs from the same biological resource base (Umana et al., 2020). This framing enables different resource streams and conversion pathways to be compared according to their maturity, feasibility, environmental contribution, and implementation requirements, rather than being described only as isolated technical options.

The potential of each valorization pathway depends on the type, quality, accessibility, and conversion suitability of the resource stream. This potential can also be assessed using quantitative indicators, such as resource availability, moisture content, net heating value, COD reduction, methane yield, electricity output, greenhouse gas abatement, investment cost, payback period, and delivered feedstock cost (Plesu Popescu et al., 2021). Therefore, the pathways should not be evaluated only by technical possibilities. A comparative assessment is needed to distinguish near-term, technically mature options, such as mill energy recovery and POME biogas, from higher-value but more demanding options, such as biochemical conversion, engineered biomaterials, and carbon products (Nasir et al., 2018; Tang et al., 2025).

### 4.1. Major Oil Palm Biomass and Residual Streams

Oil palm production generates biomass throughout the life cycle of the crop (Table 2). In the plantation phase, major biomass streams include fronds and trunks. Fronds are produced regularly during harvesting and pruning, while trunks become available in large volumes during replanting (Pulingam et al., 2022; Wahab et al., 2022). In the milling phase, the main solid residual streams include empty fruit bunches, mesocarp fiber, and palm kernel shells. Mills also generate liquid residues, particularly POME, during oil extraction and clarification (Sulin et al., 2025).

**Table 2.** Major oil palm biomass and residual streams, their main sources, general characteristics, and broad valorization potential.

| Biomass/ residual stream | Main source | General characteristics | Common current use | Valorization potential | References |
|---|---|---|---|---|---|
| Fronds | Plantation pruning and harvesting | Lignocellulosic, bulky, low loose bulk density (~100–150 kg/m$^3$), low NHV (~14–16 MJ/kg) | Mulching, field return | Compost, fiber products, bioenergy | (Nabila et al., 2023; Wahab et al., 2022) |
| Trunks | Replanting operations | Woody biomass, large volume, moderate loose density (~200–300 kg/m$^3$), NHV (~15–17 MJ/kg) | Field disposal, limited reuse | Panels, fibre materials, bio-based products | (Nabila et al., 2023; Pulingam et al., 2022) |
| Empty fruit bunches | Milling process | Moist, fibrous and bulky, high moisture (> 60%); as-received NHV (~8–10 MJ/kg) | Mulching, composting | Biochar, biomaterials, bioenergy, soil amendments | (Chia et al., 2024; D. W. K. Chin et al., 2021) |
| Mesocarp fiber | Milling process | Fibrous, combustible, relatively low moisture after milling;dry-basis NHV (~17–19 MJ/kg) | Boiler fuel | Energy, carbon materials, industrial fibre use | (Ahmad et al., 2024; Mohd Faizal et al., 2018) |
| Palm kernel shells | Milling process | Dense, carbon-rich solid; loose bulk density (~600–700 kg/m$^3$), dry-basis NHV (~18–20 MJ/kg) | Fuel use | Activated carbon, solid fuel, carbon products | (Ahmad et al., 2024; Mohd Faizal et al., 2018) |
| Palm oil mill effluent (POME) | Milling process | Liquid organic effluent, with high COD/BOD, negligible NHV in raw form | Wastewater treatment | Biogas, biomethane, emissions reduction | (Akuma et al., 2026; Kurniawan et al., 2025; Manikandan et al., 2026; Yong et al., 2023) |

Note: NHV: net heating value; COD: chemical oxygen demand; BOD: biochemical oxygen demand. Values are indicative ranges compiled from the cited sources. Bulk density values refer to approximate loose/as-received biomass density unless otherwise stated. NHV values for fronds, trunks, mesocarp fibre and palm kernel shells refer mainly to dry or air-dried solid biomass, whereas the EFB range reflects high-moisture as-received material; moisture correction is therefore needed before engineering design or economic calculation.

Each resource stream has distinct characteristics. Fronds, trunks, and empty fruit bunches are mainly lignocellulosic in nature, and they can support several forms of biological, thermochemical, or material conversion (Nabila et al., 2023; Tan et al., 2022). Mesocarp fiber and palm kernel shells are often easier to handle in energy systems because of their combustion properties (Mohd Faizal et al., 2018). Palm oil mill effluent differs from these solid streams because it is a liquid organic waste with high treatment demand and strong energy recovery potential (Akuma et al., 2026).

It should be emphasized that these streams should not be viewed solely as residues to be disposed of. They represent a diverse portfolio of renewable feedstocks (Terry et al., 2021). Some streams can support direct agricultural reuse, such as mulching or composting. Other streams can be converted into bioenergy, biomaterials, carbon-rich products, or industrial intermediates. Their fuller utilization can reduce waste, improve resource efficiency, and create additional value within the palm oil supply chain (Nasir et al., 2018; Sulin et al., 2025).

However, not all streams can be valorized in the same way. Moisture content, bulk and energy density, cost, emissions of logistics, and seasonal availability all affect economic feasibility. Therefore, successful utilization depends not only on technical suitability but also on logistics, scale, and market demand (Nabila et al., 2023; Obi, 2015). Sometimes, pretreatment is important to maximize the recovery of the components in the biomass (Chia et al., 2024; D. W. K. Chin et al., 2021). This means that biomass valorization should be approached as both a technological and a feasible challenge.

### 4.2. Comparative Evaluation of Major Valorization Pathways

A comparative view shows that whole palm valorization is not a single pathway but a portfolio of options with different readiness levels and implementation requirements. Pathways that are already embedded in mill operations, such as mesocarp fibre and palm kernel shell combustion, generally have higher technical maturity and lower implementation risk, but their value addition is often limited. In contrast, pathways such as biorefineries, engineered biomaterials, and advanced carbon products may offer higher downstream value, but require stronger feedstock quality control, preprocessing, investment, product standards, and market offtake arrangements. Based on recent literature on palm oil circular bioeconomy, biomass utilization, POME recovery, thermochemical conversion, biocomposites, biorefinery development, and carbon-based products, Table 3 compares the major whole palm valorization pathways according to technical maturity, economic feasibility, environmental benefit, logistical constraint, and implementation potential.

**Table 3.** Comparative assessment of major whole palm valorization pathways.

| Pathway | Main resource stream | Technical maturity | Economic feasibility | Environmental benefit | Logistical constraint and implementation potential | References |
|---|---|---|---|---|---|---|
| Field return, mulching, compost and soil amendment | Fronds, trunks, EFB, POME, sludge/digestate | High for field return and composting | Low to moderate direct revenue; useful for nutrient recycling and soil management | Reduces disposal pressure and supports nutrient cycling, but emissions depend on management practice | Low transport need when used on site; high near-term potential, especially for smallholders and estates | (Ahmad et al., 2024; Cheah et al., 2023; Rendón-Camargo et al., 2026; Sulin et al., 2025) |
| Mill heat and power recovery | MF and PKS | High; already widely used in boilers | High when used internally because it offsets mill energy demand; MF use for in-house electricity generation was reported at 92.4% in Peninsular Malaysia mills | Offsets fossil energy and improves mill energy self-sufficiency | Limited by boiler efficiency, competing PKS markets, and relatively low product diversification; high implementation potential | (Ahmad et al., 2024; Cheah et al., 2023; Rendón-Camargo et al., 2026) |
| POME anaerobic digestion, biogas and biomethane | Palm oil mill effluent | Medium to high; commercial systems are available but adoption remains uneven | Moderate; viability depends on POME volume, energy offtake, tariff structure, capital expenditure, and operational stability | High climate benefit; COD reduction of up to 91% biogas production reaching 325,292 $m^3$ $month^{-1}$, and greenhouse gas (GHG) reduction of 1,131 $tCO_2$-eq $month^{-1}$ | Needs covered lagoons or digesters, gas handling, grid/offtake access, and skilled operation; high potential for medium and large mills | (Akuma et al., 2026; Manikandan et al., 2026; Sulin et al., 2025) |
| Biochar, solid fuel and thermochemical products | EFB, PKS, fronds, trunks | Medium; pyrolysis, torrefaction, and carbonization are technically established but project economics vary | Moderate; stronger for drier and denser feedstocks such as PKS than for wet EFB unless preprocessing is available | Can improve carbon retention, soil amendment potential, and fossil fuel substitution | Moisture, bulk density, drying cost, and transport distance are major constraints; medium implementation potential through regional biomass hubs | (Nabila et al., 2023; Rendón-Camargo et al., 2026; Yulistiani et al., 2025) |

**Table 3.** *Cont.*

| Pathway | Main resource stream | Technical maturity | Economic feasibility | Environmental benefit | Logistical constraint and implementation potential | References |
|---|---|---|---|---|---|---|
| Biomaterials, panels, fibres and biocomposites | Trunks, fronds, EFB fibre, mesocarp fibre | Medium; product development is advancing but quality control is critical | Moderate to high where stable offtake and product standards exist | May substitute wood or fossil-based materials and increase downstream value | Requires segregation, drying, fibre processing, standards, and product certification; medium potential through industrial clusters | (Ahmad et al., 2024; Aisyah et al., 2024; Rendón-Camargo et al., 2026) |
| Biochemical and integrated biorefinery products | EFB, trunks, fronds, POME-derived organics | Low to medium; promising but less commercially mature than energy recovery | Potentially high value, but high capital expenditure and pretreatment costs increase operational and financial risk | Can create higher value chemicals, sugars, fuels, and circular intermediates | Require stable feedstock supply, pretreatment process integration, and long-term offtake; longer-term potential | (Cheah et al., 2023; Jailani et al., 2025; Rendón-Camargo et al., 2026) |
| Activated carbon and advanced carbon products | PKS. EFB biochar, carbon-rich residues | Medium to high for activated carbon; lower for advanced materials | Potentially high for PKS due to density and carbon content | Supports higher-value carbon utilization and may reduce low-grade combustion dependence | Requires controlled carbonization/activation, product quality assurance, and market access; medium to high potential for suitable feedstocks | (Saefumillah et al., 2026; Saleh et al., 2025) |

Note: MF: mesocarp fibre; PKS: palm kernel shells ; EFB: empty fruit bunches; POME: palm oil mill effluent; COD: chemical oxygen demand. This comparison indicates that implementation should be sequenced rather than treated as a uniform transition. Mature, low-risk options can be expanded first to improve resource efficiency, while higher-value biorefinery and biomaterial pathways should be developed through demonstration plants, feedstock aggregation, product standards and market-building measures. In this sense, whole palm valorization is most practical when it combines immediate resource recovery with longer-term industrial upgrading.

### *4.3. Palm Oil Mill Effluent (POME), Energy Recovery, and Emissions Reduction*

Palm oil mill effluent (POME) is one of the most important residual streams in the palm oil industry because it is generated continuously during sterilization, clarification, and hydrocyclone processes (Akuma et al., 2026). Quantitatively, about 700 kg of POME can be generated for every tonne of fresh fruit bunches processed, and Malaysia has been estimated to generate approximately 50–75 million $m^3$ of POME annually. This stream contains high organic matter, COD, and BOD, making untreated or poorly controlled POME treatment a major source of pollution and methane emissions (Manikandan et al., 2026; Mohammad et al., 2021).

At the same time, POME offers one of the clearest opportunities for measurable resource recovery. When POME is integrated into an anaerobic digestion, biogas recovery, or biomethane upgrading system, it becomes a feedstock for a mill-based resource-recovery pathway rather than a biorefinery by itself. Anaerobic digestion can convert its organic content into biogas for heat and electricity generation (Sodri & Septriana, 2022). A techno-economic and environmental assessment of a POME-based biogas plant reported COD reduction of up to 91% biogas production of 325,292 $m^3$ $month^{-1}$ with 55% methane content, and electricity generation of 696,163 kWh $month^{-1}$ (Sodri & Septriana, 2022). These figures illustrate why POME biogas should be considered a relatively mature and high-impact pathway within whole palm valorization (Akuma et al., 2026). In this way, POME can be viewed as a strategic resource-recovery stream within whole palm valorization because it connects waste treatment, renewable energy generation, and emissions reduction within a single system.

This pathway shows how environmental management can be linked directly to economic and carbon value creation. In the same case study, the biogas plant reduced greenhouse gas emissions by 1,131 tonnes $tCO_2$-eq $month^{-1}$, although profitability remained sensitive to plant loading, electricity sales, and operational efficiency, with an internal rate of return of 6.75% and a payback period of 10.8 years under the observed operating conditions (Sodri & Septriana, 2022). This suggests that POME biogas has strong environmental value, but its economic performance depends on sufficient feedstock volume, reliable power offtake, and supportive tariff or carbon-credit mechanisms (Naidu & Moorthy, 2021).

Even so, implementation remains uneven across the industry. Some mills lack the capital, infrastructure, or technical capacity needed for digestion, gas cleaning, power generation, or biomethane upgrading. Other mills may not obtain sufficient return if POME volume is low, grid access is weak, or energy purchase agreements are uncertain (Akuma et al., 2026; Manikandan et al., 2026).

### *4.4. Circular Resource Use and Carbon-linked Value Creation*

Circular resource use and carbon-linked value creation provide an important foundation for whole palm valorization. A circular approach seeks to reduce waste by keeping materials, nutrients, and energy in productive use for as long as possible (Sulin et al., 2025). In the oil palm industry, this means that biomass and residual streams should be managed as reusable resources rather than discarded outputs. When combined with methane capture, renewable energy generation, soil amendment, and material substitution, circular resource use can also support lower-emission production and climate-linked value creation. This approach improves system efficiency and supports more sustainable production practices (Siagian et al., 2024).

Several circular pathways are possible in palm-based production systems. Organic residues can return to the field as mulch, compost, or soil amendment. Solid biomass can be converted into energy, carbon materials, or industrial feedstocks. Liquid and solid streams can also be linked through integrated treatment systems that recover energy and nutrients (Cheah et al., 2023). These pathways help close material loops and reduce losses across the plantation-mill system (Cheah et al., 2023; Lau et al., 2024).

Circular resource use also changes how value is understood in the industry. In a conventional oil-centered model, value is measured mainly through oil yield and extraction efficiency. In a circular model, value also includes nutrient recovery, waste reduction, energy reuse, and the production of secondary outputs (Siagian et al., 2024; Sulin et al., 2025). This broader understanding is important because it reflects the full resource base of the crop and not only its primary oil fraction.

However, circularity requires more than technical potential. A circular system depends on coordination between estates, mills, processors, and end users. It also depends on practical systems for collection, segregation, processing, and market delivery. Without these connections, many circular pathways remain fragmented or limited to small-scale practice (Kaniapan et al., 2021). Whole palm valorization, therefore, benefits from circular thinking because circular systems create the conditions under which dispersed residues can become stable and productive value chains. Carbon management has become an important part of the global discussion on agricultural and industrial sustainability. The oil palm industry is increasingly affected by this shift because emissions performance now influences market access, investor confidence, and public credibility (Ali et al., 2025; Murphy et al., 2021). As a result, carbon is no longer only an environmental issue for the sector. Carbon is also becoming an economic and strategic issue (Murphy et al., 2021).

The oil palm industry has several pathways for climate-linked value creation. Some pathways reduce emissions directly, while others improve the efficiency of biomass and residual resource use. Methane capture from POME is one of the clearest examples because it can lower greenhouse gas emissions while also generating useful energy (Manikandan et al., 2026). Quantitative evidence from POME biogas projects shows that emissions reductions can be substantial at the mill scale, with one case reporting a reduction of 1,131 tonnes $CO_2$-eq month$^{-1}$ from POME treatment (Sodri & Septriana, 2022). Improved handling of biomass and organic residues can also reduce unmanaged decomposition and support lower-emission production systems, while enabling the co-production of value-added products (Rendón-Camargo et al., 2026). In addition, the use of oil palm biomass as a renewable feedstock may help reduce dependence on fossil-based materials and energy in selected applications (Gourich et al., 2023).

These opportunities matter because they connect environmental improvement with industrial upgrading. When mills recover methane, when biomass is used more efficiently, or when residues are converted into higher-value products, the industry can improve both sustainability performance and economic output (Siagian et al., 2024). This connection is especially important in a sector that is often judged through both productivity and environmental accountability. Therefore, carbon-related value creation fits naturally within the broader logic of whole palm valorization.

Carbon markets may also offer new possibilities for the oil palm industry. In principle, verified emission reductions from methane capture, renewable energy use, or improved waste management could generate carbon-related revenue. This prospect is attractive because it may help support investments that would otherwise be difficult to justify through conventional returns alone. In this sense, carbon finance may become a useful complement to biomass valorization and low-carbon upgrading.

However, carbon opportunities also require caution. Carbon projects are technically demanding and institutionally sensitive as they involve complex regulatory requirements, coordination across multiple institutions, and the need to ensure stakeholder acceptance. They require clear baselines, credible methodologies, reliable monitoring, and transparent reporting. Weak project design can lead to poor-quality credits, limited economic return, or reputational risk. These risks are especially important in industries where sustainability claims are already closely scrutinized (Delacote et al., 2024; Noviyanto et al., 2026). Therefore, carbon-linked value creation should be approached through strong technical standards and careful governance rather than through overly simplified market expectations (K. N. R. Kumar, 2025).

The sector also needs to consider who benefits from these opportunities. Larger estates and integrated mill operators may be better positioned to adopt carbon-related projects because they have better access to infrastructure, finance, and technical support. Smaller mills and smallholders may find it harder to participate unless aggregation mechanisms or shared systems are available (Rajakal et al., 2024). This issue matters because uneven participation can limit the wider development of climate-linked initiatives.

Overall, carbon opportunities should be understood as part of the broader whole palm valorization transition rather than as a separate agenda. They are not separate from questions of biomass use, waste management, and industrial modernization. Instead, they are closely linked to how the industry manages biomass, effluent, energy recovery, waste reduction, and product diversification. If developed with credible measurement, reporting, verification, and inclusive governance, these opportunities can strengthen the role of whole palm valorization in building a more resilient, resource-efficient, and lower-emission palm oil industry.

## 5. Implementation Challenges and Governance Priorities

Despite its strong potential, whole palm valorization has not progressed evenly across the palm oil industry. Many resource streams are available in large volumes, but their conversion into stable value chains remains limited. This gap shows that technical potential alone is not enough. Implementation also depends on logistics, commercialization pathways, policy coordination, financing, standards, and inclusive participation (Akuma et al., 2026).

### *5.1. Logistical and Commercial Barriers*

Logistics remains one of the most important barriers. Many biomass streams are bulky, wet, scattered, and costly to transport (Pulingam et al., 2022). Empty fruit bunches, fronds, and trunks often require preprocessing before they can be moved efficiently into downstream applications (Saleh et al., 2025). This requirement increases handling costs and reduces economic feasibility, especially when collection points and processing facilities are far apart. As a result, some resources remain underused even when promising technologies are available.

Concrete resource characteristics illustrate this barrier. Empty fruit bunches are typically produced as a moist and bulky stream with moisture above 60% and as-received NHV of about 8–10 MJ $kg^{-1}$, whereas palm kernel shells have a higher loose density of about 600–700 kg $m^3$ and NHV of about 18–20 MJ $kg^{-1}$ (Mohd Faizal et al., 2018; Nabila et al., 2023). As a result, palm kernel shells can enter fuel and carbon-product markets more easily, while empty fruit bunches often require drying, shredding, densification, or on-site use before they become economically attractive for longer-distance transport. This example shows that logistics barriers are linked to measurable feedstock properties, not only to general supply-chain weakness.

Commercialization also remains weak in many parts of the sector. Research and pilot projects have demonstrated many possible uses for oil palm biomass and residual streams (Nabila et al., 2023; Rendón-Camargo et al., 2026). However, large-scale adoption has been much slower. Investors often face uncertainty about feedstock consistency, product quality, technology performance, and long-term market demand. This uncertainty creates a gap between laboratory success and commercial deployment. In many cases, the industry still lacks stable offtake mechanisms, such as long-term purchase agreements, needed to support wider investment (Akuma et al., 2026; Mohamad Zaki et al., 2025).

The POME biogas pathway also illustrates the commercialization challenge. Although one case generated 696,163 kWh $month^{-1}$ and reduced emissions by 1,131 tonnes $CO_2$-eq $month^{-1}$, the same study reported an internal rate of return of 6.75% and a payback period of 10.8 years under observed conditions (Sodri & Septriana, 2022). This suggests that even technically proven pathways may require supportive tariffs, energy-purchase agreements, carbon-credit access, or concessional finance to become widely attractive.

Policy fragmentation creates another barrier. Different parts of the oil palm value chain often fall under different regulatory and policy domains (Putri et al., 2022). Agriculture, biomass utilization, renewable energy, waste management, and industrial development are not always governed through a single coordinated framework. This separation can weaken implementation because one part of the system may move forward while another remains underdeveloped. A project may be technically ready, but supporting regulations, market incentives, or infrastructure planning may still lag behind.

The transition also faces uneven participation across stakeholders. Larger estates, mills, and integrated companies usually have better access to capital, infrastructure, and technical support. Smallholders and smaller mills may not have the same capacity to adopt new technologies or enter emerging value chains (Iyai et al., 2024). This imbalance matters because smallholders contribute significantly to oil palm production in many regions (Ogahara et al., 2022). If they remain excluded, the broader benefits of the whole palm valorization will be limited.

Market development remains another challenge. Some biomass-based products still face weak demand, uncertain pricing, or strong competition from conventional alternatives (Cheah et al., 2023). Buyers may hesitate when supply is inconsistent or when quality standards are not clearly established. These problems can discourage investment even when resource availability is high (Murphy et al., 2021). Therefore, successful valorization depends not only on production capacity, but also on market confidence and product acceptance.

Taken together, these barriers show that whole palm valorization is not simply a matter of converting residues into products. The transition requires coordinated systems that can support feedstock supply, technology adoption, commercial investment, and broad participation. Without these supporting conditions, many valorization pathways will remain technically attractive but operationally limited (Kaniapan et al., 2021).

### *5.2. Policy and Governance Priorities*

The shift from oil extraction to whole palm valorization requires more than technological innovation. It also depends on clear policy direction and effective governance (Zachlod et al., 2025). These elements are essential because the oil palm industry operates across agriculture, milling, energy, waste management, manufacturing, trade, and climate-related policy domains (Ayompe et al., 2025). If these areas remain poorly connected, the transition will move slowly and unevenly.

The first priority is to strengthen the productive base of the industry (Table 4). Whole palm valorization does not replace the need for strong plantation performance. Replanting, better planting materials, improved agronomic management, and suitable mechanization remain important because they shape the long-term quality and stability of biomass and residual resources. A productive upstream sector creates a stronger foundation for downstream valorization (Murphy et al., 2021; Siagian et al., 2024).

**Table 4.** Implemented-oriented policy and governance priorities for repositioning the palm oil industry from oil extraction to whole palm valorization.

| Priority area | Practical implementation and stakeholder roles | Expected outcome | References |
|---|---|---|---|
| Upstream productivity and replanting | Use staged replanting support, improved planting materials, agronomic extension, and selective mechanization. Lead roles: plantation agencies, MPOB, estate owners, smallholder authorities, cooperatives, and financial institutions. | Higher CPO yield $ha^{-1}$; reduced ageing-palm area; better biomass quality and predictable supply. | (Ayompe et al., 2025; Murphy et al., 2021; Siagian et al., 2024) |
| Biomass logistics and aggregation | Develop regional biomass hubs for collection, drying, shredding, storage, and transport near mill clusters. Lead roles: mills, estate groups, logistics firms, local governments, and technology, and technology providers | Lower delivered feedstock cost; stable EFB/frond/ trunk supply; reduced unmanaged residues. | (Kaniapan et al., 2021; Pulingam et al., 2022; Saleh et al., 2025) |
| Commercialization and market offtake | Move from pilot studies to demonstration projects with product standards, blended finance, and long-term purchase agreements. Lead roles: industry consortia, investors, universities, technology developers, and downstream buyers | Demonstration plants; signed offtake agreements; product specifications; improved NPV/payback | (Hassan et al., 2024; Mohamad Zaki et al., 2025; Putri et al., 2022) |
| POME biogas and carbon value creation | Prioritize covered lagoons or anaerobic digesters at mills with sufficient POME volume, linked to power purchase, biomethane use, or verified carbon credits. Lead roles: mills, energy regulators, utilities, carbon-standard bodies, and environmental agencies. | COD/BOD reduction; kWh generated; methane captured; $tCO_2$-eq avoided; verified MRV reports. | (Akuma et al., 2026; Manikandan et al., 2026; Sodri & Septriana, 2022) |
| Policy alignment across sectors | Prepare a whole-palm roadmap linking agriculture, energy, waste, industry, and climate policies with clear incentives and permitting pathways. Lead roles: federal and state agencies, industry boards, certification bodies, and investment agencies | Aligned incentives; faster approvals; clearer rules for biomass, biogas, biochar, and carbon claims. | (Bathaei & Štreimikienė, 2023; Putri et al., 2022; Zachlod et al., 2025) |
| Smallholder and small-mill inclusion | Use cooperative supply models, shared preprocessing facilities, extension support, and aggregation contracts. Lead roles: smallholder organization, cooperatives, mills, NGOs, and development finance institutions. | Smallholders participating; shared facility use; additional residue income; equitable benefit distribution. | (Ayompe et al., 2025; Iyai et al., 2024; Ogahara et al., 2022) |
| Traceability, standards and assurance | Develop traceability systems and product standards for biomass-derived products and carbon claims. Lead roles: certification bodies, standards agencies, mills, manufacturers, and auditors | Documented feedstock origin; verified sustainability claims; improved buyer confidence and export readiness. | (Delacote et al., 2024; Noviyanto et al., 2026; Santos et al., 2026) |

Note: MPOB: Malaysian Palm Oil Board; POME: palm oil mill effluent; NGO: non-governmental organization; CPO: crude palm oil; EFB: empty fruit bunches; NPV: net present value; MRV: monitoring, reporting and verification; COD: chemical oxygen demand; BOD: biochemical oxygen demand; $tCO_2$-eq = tonnes of carbon dioxide equivalent; $ha^{-1}$ = per hectare; kWh = kilowatt-hour.

A second priority is to improve the enabling environment for biomass and residual resource use through physical logistics infrastructure. This should include regional biomass hubs located near mill clusters, where empty fruit bunches, fronds, trunks, fibre, and shells can be collected, shredded, dried, densified, stored, and dispatched according to downstream product requirements.

Mills and estate groups can provide feedstock data and primary handling facilities; logistics companies can manage transport and storage, while state agencies can support land allocation, infrastructure planning, and permitting. This would directly address one of the most persistent barriers to whole palm valorization: the mismatch between dispersed, bulky biomass supply and centralized industrial demand. Policy support should extend beyond conversion technologies alone and also cover collection systems, preprocessing facilities, storage, transport, and feedstock coordination (A. Kumar et al., 2025). A third priority is to create stronger alignment across policies through a dedicated whole-palm valorization roadmap. Such a roadmap should connect agricultural productivity programmes, biomass utilization incentives, renewable-energy tariffs, waste regulations, industrial upgrading funds, and climate-policy instruments. The practical purpose is to prevent a situation in which one agency promotes biomass use while another imposes unclear waste-handling, grid-access, or permitting requirements. Clear inter-agency coordination would give mills, investors, and technology providers greater confidence to plan long-term projects (Bathaei & Štreimikienė, 2023). Governance should also actively support commercialization by bridging the gap between research outputs and bankable projects (Putri et al., 2022). Public support can be channeled into demonstration plants that evaluate real feedstock variability, product quality, logistics cost, and buyer acceptance under commercial conditions. Universities and research institutes can validate process performance; mills can provide feedstock and operational sites; technology providers can supply conversion systems; and industrial buyers can define product specifications. This approach would move valorization beyond laboratory feasibility toward investment-ready deployment (Hassan et al., 2024; Putri et al., 2022).

### *5.3. Inclusion, Traceability and Carbon Governance*

Inclusion should be treated as a policy priority because smallholders and smaller mills may not have the capital, infrastructure, or technical capacity to participate individually (Ayompe et al., 2025; Kaniapan et al., 2021). Cooperative supply models, shared preprocessing facilities, cluster-based aggregation, extension support, and residue-purchase contracts can create practical entry points for these groups. Extension agencies and cooperatives can help standardize collection and quality practices, while mills and buyers can offer transparent pricing mechanisms. Without these arrangements, whole palm valorization risks becoming concentrated among large integrated operators rather than generating broader sector-wide benefits.

Carbon-related initiatives also require careful governance through measurable, reportable, and verifiable systems. For POME biogas and other emissions-reduction projects, implementation should specify baselines, methane capture measurements, electricity or biomethane output, fugitive emissions, and third-party verification. These requirements are essential because weak carbon accounting can damage credibility and reduce investor confidence. Carbon value creation should therefore be treated as part of sector-wide monitoring and assurance rather than as an isolated revenue opportunity.

Overall, policy and governance must help reposition the palm oil industry as a more integrated and resource-efficient system (Putri et al., 2022; Yuslaini et al., 2026). Effective implementation requires assigned responsibilities, operational infrastructure, investment mechanisms, measurable indicators, and coordinated standards. In practical terms, whole palm valorization will advance only when upstream productivity, biomass logistics, downstream markets, carbon governance, and inclusion mechanisms are developed together rather than through isolated initiatives.

## 6. Future Directions for Research and Industrial Development

Future research should move beyond identifying general resource potential and focus more on implementation under real operating conditions. Many studies have already shown that oil palm biomass and residual streams can support a wide range of applications (Kaniapan et al., 2021; Saleh et al., 2025; Terry et al., 2021). However, fewer studies explain which pathways remain most feasible at commercial scale, under which conditions, and for which types of producers. This gap needs more attention because industrial decisions depend on practical performance rather than technical promise alone.

Research should also adopt a stronger systems perspective. Many studies still examine individual biomass streams or technologies in isolation. This approach is useful for early-stage development, but it does not fully reflect the complexity of the oil palm production system. In practice, the value of one stream may depend on how other streams are handled, combined, or prioritized. For example, allocating biomass to energy production rather than material or biochemical applications can lead to different economic and environmental trade-offs. Future work should therefore examine how plantation residues, mill by-products, energy recovery systems, carbon-linked pathways, and downstream processing routes can function together within an integrated valorization framework (Akuma et al., 2026). In this more technical context, exergy-based indicators may also be useful. An exergy footprint can be understood as an indicator of the useful energy or resource quality consumed, degraded, or lost in delivering a given process output, and it should be reported together with economic and environmental metrics rather than used in isolation. Applying a combination of Energy Quality Pinch (H. H. Chin et al., 2023) targeting and P-graph based network optimization is therefore a promising option that deserves further attention (W. Ng et al., 2025).

Economic assessment should become more detailed and more consistent. Technical feasibility does not always translate into commercial viability (Makepa et al., 2023). Future studies should therefore report comparable quantitative indicators, including delivered feedstock cost, moisture-adjusted energy value, preprocessing cost, product yield, capital expenditure, operating cost, net present value, internal rate of return, payback period, greenhouse gas abatement cost, and market price sensitivity. Comparative analysis across different valorization pathways will also be useful because mill energy recovery, POME biogas, empty fruit bunches biochar, biomaterials, and biochemical conversion differ substantially in maturity, risk, and value creation potential (International Renewable Energy Agency, 2022).

Industrial development should also become more strategic. The sector does not need to commercialize every possible biomass application at once. Instead, it should identify priority pathways that match local feedstock conditions, infrastructure capacity, policy direction, and market opportunities. Mature pathways such as MF/PKS energy recovery and POME biogas can be prioritized for near-term resource efficiency and emissions reduction, while empty fruit bunches-based biomaterials, biochar, and biochemical platforms can be developed through regional demonstration hubs (Kaniapan et al., 2021; Siagian et al., 2024). A more selective strategy will improve the chances of successful scale-up and avoid spreading investment too thinly across poorly integrated projects.

Future work should also give greater attention to inclusive participation. Smallholders and smaller mills are important parts of the oil palm landscape, but they often have limited access to capital, technology, and downstream value chains (Ogahara et al., 2022). Research and industrial planning should therefore explore models that reduce these barriers. Shared biomass hubs, cooperative supply systems, cluster-based processing, and joint investment platforms may provide more practical entry points for smallholders. These models deserve closer study because they can make whole palm valorization more workable and more equitable (Ayompe et al., 2025).

Finally, future development should pay closer attention to standards, traceability, and market confidence. Biomass-based and low-carbon products will face stronger competition if quality remains inconsistent or if claims are poorly supported. Research should therefore contribute not only to process innovation, but also to methods for product assurance, environmental assessment, and transparent performance reporting (Santos et al., 2026). These elements will be important for building trust among regulators, investors, industrial users, and export markets.

## 7. Conclusion

The oil palm industry has reached a stage where oil extraction alone is no longer sufficient to support long-term resilience and competitiveness. Although the sector remains economically important, it now faces growing pressure from stagnant yields, ageing plantations, labor constraints, slow replanting, and rising environmental expectations. This review shows that whole palm valorization offers a broader framework for addressing these challenges by expanding the role of the industry beyond edible oil production to include biomass utilization, renewable materials, energy recovery, nutrient recycling, carbon-linked value creation, and resource-efficient production pathways.

The key contribution of this review is the integrated whole-palm framing, which moves the discussion from isolated biomass or waste-utilization options toward a connected assessment of plantation residues, mill residues, POME, energy recovery, carbon-linked value, downstream markets, and governance requirements. By defining whole palm valorization within the plantation-mill boundary, this review clarifies how the concept differs from, while connecting with, biomass utilization, circular bioeconomy, biorefinery development, and carbon value creation. It also clarifies that downstream post-consumer streams such as used cooking oil fall outside the core boundary of whole palm valorization and are better treated as related circular-bioeconomy boundary cases. The comparative assessment shows that valorization pathways are not equal in maturity or feasibility. Field return, composting, and mill energy recovery are relatively mature but often generate modest downstream value; POME biogas offers strong and quantifiable climate benefits when feedstock volume and energy offtake are sufficient; while biomaterials, biochar, advanced carbon products, and biochemical platforms require stronger logistics, preprocessing, standards, and market development. Therefore, the future of the oil palm industry will depend not only on technological innovation, but also on stronger coordination across plantation management, biomass logistics, downstream processing, finance, carbon governance, and smallholder inclusion. Overall, whole palm valorisation provides an important pathway for enhancing economic resilience, strengthening downstream value creation, and supporting a more resource-efficient and sustainable palm oil industry.

Moving forward, policymakers should prioritize a coordinated whole-palm valorization roadmap that links biomass logistics, POME biogas deployment, carbon governance, product standards, and smallholder inclusion, while researchers should focus on comparative pathway-level techno-economic and environmental assessments to identify the most feasible and scalable valorization options. These actions would make whole palm valorization more measurable, investment-ready, and inclusive.

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**Abbreviations**

The following abbreviations are used in this manuscript:

| | |
|---|---|
| POME | Palm Oil Mill Effluent |
| SDGs | Sustainable Development Goals |
| CPO | Crude Palm Oil |
| EFB | Empty Fruit Bunches |
| MF | Mesocarp Fibre |
| COD | Chemical Oxygen Demand |
| BOD | Biochemical Oxygen Demand |
| NHV | Net Heating Value |
| PKS | Palm Kernel Shells |
| MPOB | Malaysian Palm Oil Board |
| NGO | Non-governmental Organization |
| MRV | Monitoring, Reporting and Verification |

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Agricultural & Rural Studies

*Review*

# Agricultural Extension for Resilient Smallholder Farming Systems: Mapping Evidence across Climate, Market, and Livelihood Shocks

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**Abstract:** Smallholder farming systems are increasingly exposed to interacting climate, market, and livelihood shocks that threaten production, food security, income stability, and long-term adaptive capacity. This study conducted a PRISMA-ScR-guided scoping review to examine how agricultural extension supports resilient smallholder farming systems across climate, market, livelihood, and compound shocks. Following PRISMA-ScR screening, 58 studies met the eligibility and relevance criteria and were retained for qualitative synthesis. Framework-based thematic analysis was used to examine shock domains, extension modalities, resilience-building mechanisms, resilience capacities, farming and livelihood outcomes, equity dimensions, and evidence gaps. The findings show that the evidence base is strongly concentrated on climate shocks, including drought, rainfall variability, floods, heat stress, pest pressure, water stress, and crop failure. Market and livelihood shocks are less systematically examined, although they appear through input–price increases, unstable markets, food insecurity, income loss, labor constraints, and gendered vulnerability. Extension was reported as supporting resilience through linked mechanisms of risk awareness, knowledge translation, social learning, access to inputs and services, market linkage, institutional brokerage, and empowerment. The strongest evidence concerns adaptive capacity and practice change, whereas absorptive and transformative capacities remain less consistently measured. The review proposes agricultural extension as a resilient infrastructure: a social and institutional system that connects farmers to knowledge, resources, markets, institutions, and collective learning. Future research should focus on mechanism-based, equity-sensitive, longitudinal, and compound-shock analyses, while policies should strengthen pluralistic extension systems that integrate climate, market, financial, digital, and livelihood advisory support.

**Keywords:** rural advisory services; climate-smart agriculture; smallholder resilience; adaptive capacity; livelihood diversification; climate information services

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## 1. Introduction

Smallholder farming systems continue to play a key role in food security, rural livelihoods, and poverty reduction, especially in low- and middle-income countries (LMICs). However, these systems are now increasingly subjected to compounding and interacting climate, market, and livelihood shocks that jeopardize production, income stability, food security, and adaptive capacity. Climate variability, drought, flooding, heat stress, pest infestations, fluctuations in input costs, market disruptions, and livelihood insecurity do not necessarily occur independently of one another but instead interact with structural limitations, including insufficient land, fragile infrastructure, limited access to credit, gender inequality and differential advisory services (Ado et al., 2019; Davis et al., 2021; P. A. Williams et al., 2018). Thus, smallholder resilience is not just about the capacity to adopt improved technology. It also requires the ability to foresee risk, withstand shocks, modify farming and livelihood strategies, and adapt vulnerable systems when established practices are no longer viable.

Agricultural extension plays an important role in this resilience agenda. Extension was once viewed mainly as technology transfer, but it is now increasingly understood as a pluralistic system of knowledge exchange, advisory support, institutional brokerage, and capacity building. It facilitates the linkage between farmers and climate information, agronomic knowledge, market opportunities, input suppliers, credit, insurance, farmer groups, and public agencies. Recent research has indicated that farmer field schools, farmer-to-farmer extension, climate information services, digital advisory services, and participatory learning methodologies can enhance the implementation of climate-smart practices, promote anticipatory decision-making, facilitate livelihood adaptation, and increase readiness for climate risks (Amadu, 2022; Antwi-Agyei et al., 2014; Nkiaka et al., 2019; Pienaah et al., 2024; Porciello et al., 2022; Staub & Clarkson, 2021). However, the effectiveness of extension depends not only on information delivery but also on trust, timeliness, local relevance, resource access, social inclusion, and farmers' capacity to act on advice.

Recent studies have improved the understanding of climate-resilient crops, climate-smart agriculture, smallholder vulnerability reduction, livelihood diversification, and smallholder adaptive capacity (Abegunde et al., 2019; Acevedo et al., 2020; Mohammed et al., 2021; T. G. Williams et al., 2020). However, there are significant constraints. First, there is a lack of systematic analysis of market shocks, livelihood shocks, and compound risks, and much of the evidence is focused on climate adaptation and technology adoption. This is problematic because climate risks frequently turn into livelihood crises due to market volatility, debt, food–price hikes, a lack of labor and access to services (Davis et al., 2021; Kuhl, 2018). Second, extension is often treated as an explanatory variable for adoption rather than as a resilience-enabling system that operates through risk communication, knowledge translation, social learning, institutional brokerage, market linkage, and empowerment. Third, there is a lack of consistency in measuring the outcomes of resilience. Awareness, participation, or adoption are frequently cited as indicators of resilience, but they are not always indicators of better food security, income stability, recovery capacity, or transformative change.

These gaps warrant a systematic mapping of the contribution of agricultural extension to resilient smallholder farming systems in the context of shocks. A scoping review is suitable in this case, as the evidence is broad, interdisciplinary, and methodologically diverse. This study aims to map the literature on agricultural extension and smallholder resilience, specifically focusing on the context of shocks related to climate, markets, and livelihoods, guided by the PRISMA-ScR guidelines. Instead of providing an estimate of one impact, the review identifies the key categories of shocks analyzed, forms of extension, pathways to resilience, and pathways to assessing resilience. The review is guided by five research questions:

RQ1. What climate, market, and livelihood shocks are addressed in studies linking agricultural extension with smallholder resilience?

RQ2. What extension models, advisory tools, and delivery mechanisms are used to support resilient smallholder farming systems?

RQ3. Through what mechanisms does agricultural extension contribute to absorptive, adaptive, and transformative resilience capacities?

RQ4. What indicators are used to assess resilience outcomes in the extension literature?

RQ5. What conceptual, methodological, geographical, and equity-related gaps remain?

By addressing these questions, this study maps the current evidence and identifies key implications for research, policy, and agricultural extension practice. This study makes three contributions. First, it reframes agricultural extension as resilient infrastructure rather than only as a technology-transfer mechanism. Second, it extends the analysis beyond climate-smart agriculture by incorporating market, livelihood, and compound shocks that shape smallholder vulnerability. Third, it links extension modalities to the three overarching resilience capacities—absorptive, adaptive, and transformative—while identifying farm-level, livelihood, and market adaptation as subdimensions of adaptive capacity and collective action as a cross-cutting mechanism.

## 2. Conceptual Background

### *2.1. Smallholder Farming Systems and Multidimensional Shocks*

Smallholder farming systems are integrated household–farm–livelihood systems shaped by land, labor, markets, ecology, social relations, and institutions (Marsden et al., 2023; Tripathi et al., 2021). Their resilience also relies on food security, income stability, asset protection, and access to services (Cohn et al., 2017; P. A. Williams et al., 2018). Smallholders are confronted with three primary shock domains and their compound or cascading combinations. Drought, flooding, cyclones, heat stress, rainfall variability, pest pressure, crop failure, and water stress are climate shocks that affect smallholder farming systems (Acevedo et al., 2020; Nkiaka et al., 2019). Market shocks encompass market access constraints, price volatility, increases in input costs, disruption in the value chain, postharvest losses, and volatile demand (Davis et al., 2021; Kuhl, 2018). Livelihood shocks include food insecurity, income loss, migration pressure, labor shortages, health shocks, conflict, and social vulnerability (Ado et al., 2019; Mohammed et al., 2021). These shocks can have a knock-on effect: drought can diminish yield, drive up food prices, deplete assets, exacerbate debts, and push people to diversify their livelihoods. Resilience must therefore be seen as a response to a combination of environmental, economic, and social pressures and not just climate risk.

### *2.2. Agricultural Extension as a Resilience-Enabling System*

Increasingly, agricultural extension is considered a pluralistic, rather than a linear, system of advice and innovation. These include public agencies, NGOs, farmer groups, cooperatives, private actors, digital platforms, climate-service providers, and community facilitators (Amadu, 2022; Porciello et al., 2022). Extension modalities include public advisory services, farmer field schools, farmer-to-farmer extension, climate information services, digital agro-advisory services, climate-smart agriculture training, value-chain extension, gender-responsive extension, participatory innovations, and livelihood and finance advisory support. Extension can function as a resilience-enabling system by helping farmers understand risk, learn, adapt, access markets, and mobilize institutional support (Nkiaka et al., 2019; Pienaah et al., 2024; Staub & Clarkson, 2021). However, extension contributes to resilience only when it is timely, trusted, locally relevant, inclusive, and connected to resources that farmers can use.

### *2.3. Resilience Capacities*

This review adopts a three-capacity framework. Absorptive capacity is the capacity to absorb shocks, underpinned by early warning systems, emergency decision-making, savings, social safety nets, food stocks, and short-term risk management (Nkiaka et al., 2019; Tamru et al., 2025). Adaptive capacity is the capacity to adjust farming and livelihood activities, including crop diversification, water management, climate-smart agriculture, livelihood diversification, market access, and new knowledge (Abegunde et al., 2019; Acevedo et al., 2020). Transformative capacity is the capacity to change structural conditions that create vulnerability, such as institutional change, collective action, gender power dynamics, finance and markets, land-use planning, farmer organizations, and long-term innovation systems (Kuhl, 2018; T. G. Williams et al., 2020). While much existing research focuses on adaptive capacity, extension can help with all three capacities.

### *2.4. Proposed Analytical Framework*

In this study, agricultural extension is conceptualized as resilient infrastructure: a social and institutional system that links smallholders to knowledge, services, markets, finance, institutions, and collective learning capacities needed to absorb, adapt to, and transform under climate, market, livelihood, and compound shocks. The analysis follows a pathway from shock exposure to extension intervention, resilience-building mechanism, resilience capacity, and farming or livelihood outcome. Climate information services (CISs) can enhance anticipatory decision-making and minimize crop loss or food insecurity due to climate shocks (Nkiaka et al., 2019; Warner et al., 2022). Value-chain extension can lead to better bargaining power, price awareness, market access, and income stability in times of market shock (Davis et al., 2021; Kuhl, 2018). Integrated advisory services in combination with credit, social protection and livelihood diversification can mitigate risks and increase adaptive or transformative capacity in relation to livelihood shocks, although this is not always the case (Ado et al., 2019; Mohammed et al., 2021). This framework takes the analysis from “Does extension lead to adoption?” to “How does extension work, under which shock conditions, for whom and with what resilience outcomes?”

The analytical framework followed in the review is summarized in Figure 1. It demonstrates how climate, market, livelihood, and compound or cascading shocks shape smallholder vulnerability; how pluralistic and integrated extension interventions respond to these interacting pressures; and how extension operates through risk awareness, knowledge translation, social learning, service access, market linkage, and empowerment. These mechanisms are likely to enhance absorptive, adaptive, and transformative capacities that in turn influence farming and livelihood outcomes.

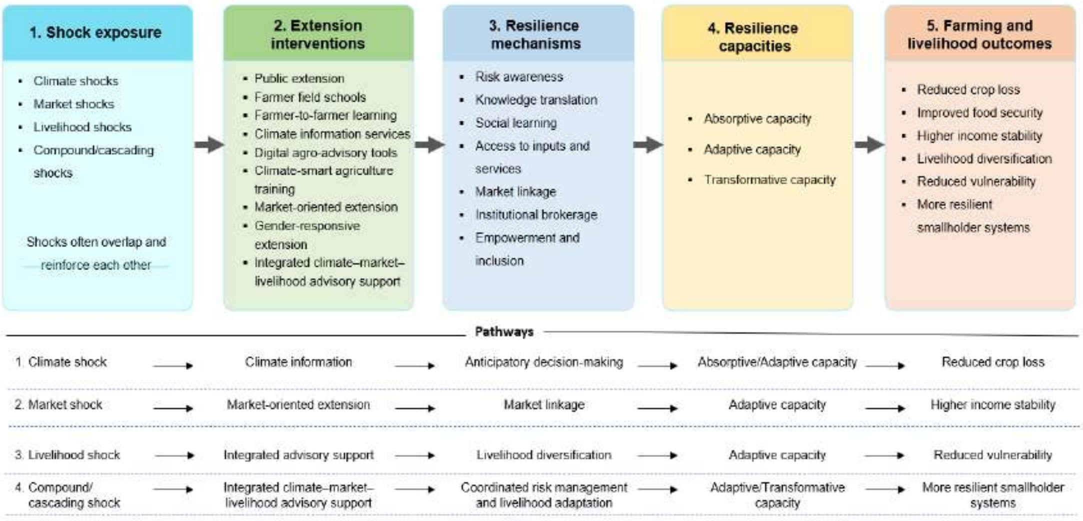


**Figure 1.** Conceptual framework of agricultural extension pathways for resilient smallholder farming systems under climate, market, livelihood, and compound shocks.

## 3. Research Methodology

### *3.1. Research Design*

A scoping review design, as suggested by the PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews), was used. Given the wide, interdisciplinary, and methodologically heterogeneous literature on agricultural extension, measures of smallholder resilience, and multidimensional shocks, a scoping review was suitable. This approach enables the study to map the range of evidence, clarify key concepts, identify dominant modalities of extension delivery, synthesize mechanisms of resilience, and identify gaps regarding shocks to climate, market, and livelihoods, which is not possible in an effectiveness review or meta-analysis (Arksey & O'Malley, 2005; Levac et al., 2010; Peters et al., 2020; Tricco et al., 2018). The review was performed in five steps: research questions, searching for relevant literature, selecting studies, charting the data, and summarizing or synthesizing the findings.

**Table 1.** Research protocol.

| **Item** | **Description** |
|---|---|
| **Research problem** | To examine how agricultural extension supports resilient smallholder farming systems across climate, market, and livelihood shocks. |
| **Review approach** | Scoping review using PRISMA-ScR guidance. |
| **Databases** | Web of Science Core Collection, Scopus, Google Scholar, and citation tracking. |
| **Search terms** | "agricultural extension," "advisory service," "farmer field school," "climate information service," "digital advisory," "smallholder," "resilience," "adaptive capacity," "climate shock," "market shock," "livelihood shock," and related terms. |
| **Time frame** | Studies published from January 1, 2000, to May 31, 2026. |
| **Geographical scope** | Global, with attention to low- and middle-income smallholder farming contexts. |
| **Types of studies** | Empirical, mixed-methods, qualitative, quantitative, review, and conceptual studies relevant to extension and smallholder resilience. |
| **Inclusion criteria** | Peer-reviewed studies focused on smallholder farmers, agricultural extension or advisory services, and resilience-related responses to climate, market, livelihood, or compound shocks. |
| **Exclusion criteria** | Studies unrelated to smallholder agriculture, studies without an extension/advisory component, purely technical agronomic studies without farmer-facing relevance, nonagricultural resilience studies, and non-English publications. |
| **Data extraction** | Author, year, country, farming system, shock type, extension modality, resilience mechanism, resilience capacity, outcome indicators, method, and key findings. |

**Table 1.** *Cont.*

| Item | Description |
| --- | --- |
| **Analytical approach** | Framework-based thematic synthesis combining deductive and inductive coding. |
| **Quality/relevance appraisal** | Assessment of methodological transparency, conceptual relevance, clarity of extension intervention, clarity of resilience outcome, and attention to equity. |

### *3.2. Search Strategy*

A multi-source search strategy was used to capture literature across agricultural extension, rural advisory services, climate adaptation, food security, livelihood diversification, and smallholder resilience. Searches were conducted in Web of Science Core Collection and Scopus and were supplemented by Google Scholar and citation tracking to identify highly relevant peer-reviewed studies not captured through database searches. The search covered studies published between 1 January 2000 and 31 May 2026. Search terms combined four concept blocks: agricultural extension and advisory systems; smallholder farming systems; resilience and adaptive capacities; and climate, market, livelihood, or compound shocks. Full database-specific search strings and search notes are provided in Supplementary Table S1.

### *3.3. Inclusion and Exclusion Criteria*

Studies were included if they met four criteria. First, they focused on smallholder farmers, small-scale producers, family farmers, or rural farming households. Second, they examined farmer-facing agricultural extension, rural advisory services, farmer training, farmer field schools, farmer-to-farmer extension, climate information services, digital advisory tools, market-oriented extension, financial advisory support, livelihood advisory support, or another knowledge-support mechanism. Third, they addressed resilience, adaptation, coping, vulnerability reduction, food security, livelihood security, livelihood diversification, recovery, or adaptive capacity. Fourth, they considered climate, market, livelihood, or compound shocks affecting farming systems or rural livelihoods. Studies were excluded if they focused only on large-scale commercial agriculture, lacked a farmer-facing extension or advisory component, addressed technical agronomic performance without learning or advisory relevance, examined non-agricultural resilience, lacked methodological or conceptual detail, were non-English publications, or were editorials, opinion pieces, news items, or book reviews.

### *3.4. Study Selection Process*

PRISMA-ScR procedures were used in the study selection process (Tricco et al., 2018). Titles and abstracts were screened for eligibility following duplicate removal. Records that appeared potentially relevant or uncertain at this stage were retained for full-text retrieval and review. The retrieved reports were then assessed to determine whether smallholder farming, extension or advisory support, and shock- or stress-related responses were substantively connected. In the full-text stage, reports were excluded when extension was only mentioned superficially or resilience was discussed without a specific advisory or knowledge-support component. The author conducted the primary screening and full-text eligibility assessment. To reduce selection bias, an independent assistant cross-checked screening decisions against the eligibility criteria. A PRISMA-ScR flow diagram was used to report the final screening process, which included identifying records, removing duplicates, screening records, assessing full texts, exclusions with reasons, and studies included in the synthesis.

### *3.5. Data Extraction*

A structured data extraction form was created to ensure that the data collection process was consistent across studies. The extraction fields included bibliographic information, publication year, journal, country/region, farming system, study population, shock type, extension modality, delivery actor, study design, data source, resilience concept, resilience capacity, outcome indicators, equity focus, and reported limitations.

Three analytical dimensions were highlighted: the nature of the shock considered, the modality of extension explored, and the type of association between extension and resilience. This enabled the review to go beyond a descriptive list of studies to consider the nature of extension, when it works and when it does not, and what the outcomes have been reported to be. The extracted data were cross-checked with the assistance of an independent assistant to minimize errors and enhance consistency. The full data-charting and extraction form is provided in Supplementary Table S2.

### *3.6. Thematic Coding Procedure*

Qualitative coding was conducted using a framework-based thematic approach that combined deductive and inductive coding. Deductive codes were derived from the research questions and analytical framework and covered seven domains: shock exposure, extension interventions, resilience mechanisms, resilience capacities, farming and livelihood outcomes, equity and contextual moderators, and evidence gaps. Inductive coding was subsequently used to identify recurring subthemes emerging from the included studies, including climate-information usability, farmer-led learning, digital exclusion, market-system linkages, gendered access to extension, livelihood diversification, and the use of adoption as a proxy for resilience. Coding decisions were cross-checked against the extracted study data and refined where necessary to maintain consistency across studies (Amadu, 2022; Azzarri & Nico, 2022; Nkiaka et al., 2019; Porciello et al., 2022; Staub & Clarkson, 2021; T. G. Williams et al., 2020). The complete thematic coding framework, including themes, subthemes, descriptions, and representative sources, is provided in Supplementary Table S4.

### *3.7. Data Analysis and Synthesis*

The coded data were analyzed in two stages. First, descriptive analysis was used to summarize publication period, geographical distribution, research design, shock domain, extension modality, and reported outcomes. Second, the coded evidence was compared across studies to identify recurring extension–resilience pathways and variations by shock context, advisory approach, mechanism, equity dimension, and outcome. The findings were then organized according to absorptive, adaptive, and transformative resilience capacities and mapped across climate, market, livelihood, and compound shocks. No pooled effect estimates were calculated because the review included conceptually and methodologically heterogeneous evidence. The analysis therefore focused on mapping patterns, relationships, and evidence gaps rather than estimating comparative effectiveness, consistent with the purpose of a scoping review (Levac et al., 2010; Peters et al., 2020).

### *3.8. Quality and Relevance Appraisal*

A formal risk-of-bias assessment was not required because this was a scoping review. However, a relevance and methodological-transparency appraisal was conducted to support the interpretation of the evidence base. Five criteria were used to assess each study: clarity of research design, clarity of the extension or advisory intervention, clarity of the resilience outcome, appropriateness of data and methods, and attention to context and equity. The appraisal was not used to exclude studies after eligibility screening; rather, it was used to interpret the strength, relevance, and limitations of the evidence.

This appraisal was necessary because several studies in this field use broad concepts such as adaptation, resilience, vulnerability, and climate-smart agriculture without clearly specifying the mechanisms through which extension supports resilience. The appraisal, therefore, helped distinguish studies that linked extension only to adoption or awareness from those that provided stronger evidence of extension-related pathways to absorptive, adaptive, transformative, or livelihood resilience (Supplementary Table S6).

### *3.9. Bias Resolution Process*

To minimize selection, coding, and interpretation bias, several procedures were used. To capture literature from across agricultural extension, climate adaptation, rural development, food security, livelihood diversification, and resilience studies, Web of Science Core Collection and Scopus were searched, supplemented by Google Scholar and citation tracking. Second, the screening process was performed in two stages: first, the titles and abstracts were screened, and then the full texts were screened for eligibility. Third, a structured extraction form was adopted to standardize the data collection. Fourth, coding decisions were cross-checked with the assistance of an independent assistant. Any differences or uncertainties were resolved by returning to the extraction form, eligibility criteria, and analytical framework. Finally, both foundational and recent studies were incorporated to ensure a balance of conceptual depth and current evidence.

## 4. Results

### *4.1. Document Selection*

The summarized PRISMA-ScR screening process is shown in Figure 2. The initial search of Web of Science Core Collection, Scopus, Google Scholar, and citation-tracking records identified 2,369 records. After removing 1,487 duplicate records, 882 records remained for title and abstract screening. At this stage, 704 records were excluded because they did not sufficiently relate to smallholder farming, agricultural extension or advisory services, resilience, climate, market, livelihood, or compound shock domains. The remaining 178 reports were assessed for full-text eligibility. Of these, 120 reports were excluded because they lacked a farmer-facing component, had an unclear resilience or shock linkage, provided limited methodological or conceptual detail, and/or focused on agronomic content without clear extension relevance. Consequently, 58 studies met the eligibility and relevance criteria and were included in the final qualitative synthesis. The characteristics of the 58 included studies are provided in Supplementary Table S3.

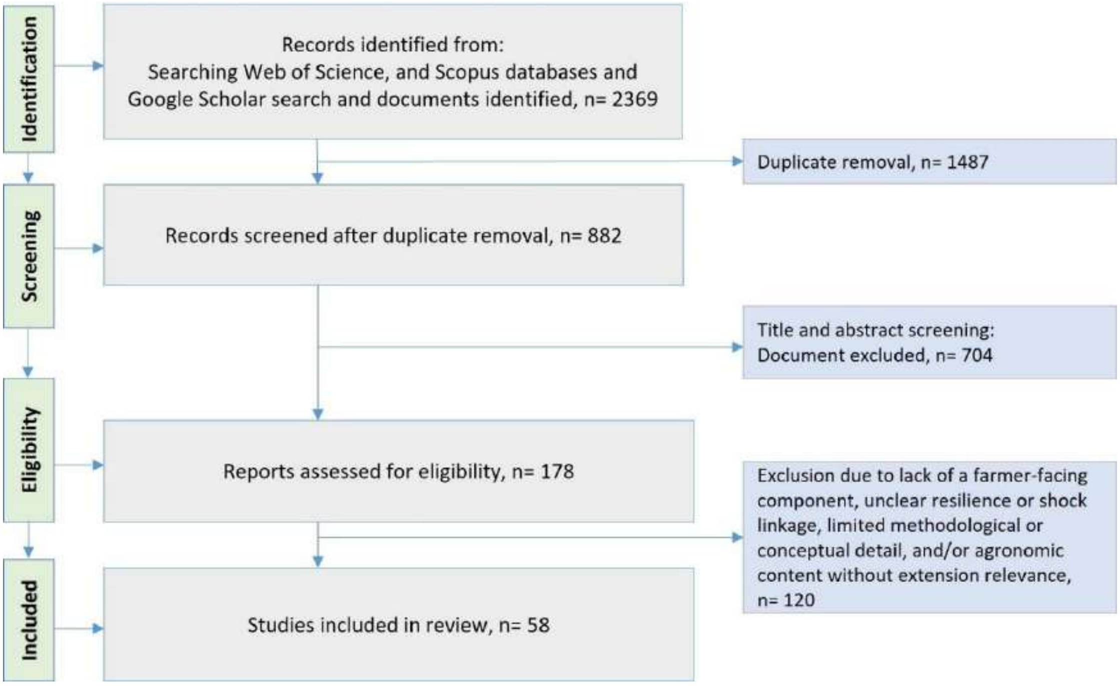


**Figure 2.** PRISMA-ScR flow diagram of study identification, screening, eligibility assessment, and inclusion.

*4.2. Descriptive Profile of the Included Studies*

The final evidence base comprised 58 studies published between 2008 and May 2026, with a clear concentration after 2018. Overall, 42 studies (72.4%) were published from 2019 onward, indicating the recent growth of scholarship linking agricultural extension with smallholder resilience. Regionally, the evidence was concentrated in Sub-Saharan Africa or Africa-focused studies (n = 29; 50.0%), followed by global or LMIC syntheses (n = 16; 27.6%), South or tropical Asia (n = 5; 8.6%), and limited Caribbean and other evidence. The geographical categories were mutually exclusive, with each publication assigned to one primary category according to its stated geographical scope. Studies focused principally on one or more African countries or on Africa as a region were classified as Sub-Saharan Africa/Africa-focused, whereas global or LMIC syntheses included evidence from multiple world regions without a predominant Africa-specific scope. Methodologically, 36 studies (62.1%) were primary empirical, participatory, or mapping studies; 15 studies (25.9%) were reviews or evidence syntheses; and 7 studies (12.1%) were conceptual or framework-oriented studies.

Climate shocks were the dominant focus, appearing in 44 studies (75.9%), followed by livelihood-related shocks or outcomes (n = 25; 43.1%), market, input, financial, or value-chain shocks (n = 16; 27.6%), and compound or cascading shocks (n = 11; 19.0%). The main extension modalities were climate-smart or adaptive agronomic extension (n = 18; 31.0%), climate information, weather, digital, or ICT advisory services (n = 16; 27.6%), market, financial, value-chain, or livelihood advisory support (n = 14; 24.1%), farmer-led or participatory extension (n = 12; 20.7%), and gender-responsive or inclusive extension (n = 7; 12.1%). The most common outcomes were adoption or adaptive practice change (n = 38; 65.5%), followed by food security, income stability, or livelihood diversification (n = 24; 41.4%), and vulnerability reduction, preparedness, recovery, or resilience measurement (n = 15; 25.9%). These patterns show a recent but uneven evidence base, with stronger attention to climate adaptation and practice change than to market shocks, livelihood shocks, compound risks, equity, and long-term resilience (Table 2).

**Table 2.** Descriptive profile of the final included studies

| Dimension | Quantified pattern |
|---|---|
| Final sample | 58 studies |
| Publication period | 2008–2014: 2 (3.4%); 2015–2018: 14 (24.1%); 2019–2021: 15 (25.9%); 2022–2026: 27 (46.6%) |
| Dominant regions | Sub-Saharan Africa/Africa-focused: 29 (50.0%); global/LMIC syntheses: 16 (27.6%); South/tropical Asia: 5 (8.6%); other: 8 (13.8%) |
| Study design | Primary empirical/participatory/mapping: 36 (62.1%); review/evidence synthesis: 15 (25.9%); conceptual/framework-oriented: 7 (12.1%) |
| Shock focus* | Climate: 44 (75.9%); livelihood: 25 (43.1%); market/input/financial/value-chain: 16 (27.6%); compound/cascading: 11 (19.0%) |
| Extension modality* | Climate-smart/adaptive agronomic extension: 18 (31.0%); climate information/weather/digital advisory: 16 (27.6%); market/financial/livelihood advisory: 14 (24.1%); farmer-led/participatory extension: 12 (20.7%); gender-responsive/inclusive extension: 7 (12.1%) |
| Main outcomes* | Adoption/adaptive practice change: 38 (65.5%); food security/income/livelihood diversification: 24 (41.4%); vulnerability reduction/preparedness/recovery/resilience measurement: 15 (25.9%); equity/empowerment/transformative capacity: 10 (17.2%) |

Note: *Multiple coding was used where studies addressed more than one shock, modality, or outcome; therefore, percentages do not sum to 100%. Geographical categories were mutually exclusive, based on each study's primary scope; global or LMIC syntheses were separated from Africa-focused studies.

*4.3. Shock Domains Addressed in The Literature*

The included studies addressed four main shock domains: climate, market, livelihood, and compound or cascading shocks (Table 3). Climate shocks dominated the evidence base, particularly drought, rainfall variability, heat stress, flooding, water stress, pest pressure, soil degradation, and crop failure. Extension responses were mainly linked to climate-smart agriculture training, farmer field schools, farmer extension facilitators, weather advisories, and climate information services, which supported adaptive practice change in seed, soil, water, crop diversification, conservation agriculture, and seasonal decision-making (Abegunde et al., 2019; Acevedo et al., 2020; Nkiaka et al., 2019; Pienaah & Luginaah, 2024; Wekesa et al., 2018). Market shocks were less directly examined, although input-price increases, output-price instability, weak bargaining power, restricted market access, postharvest losses, and value-chain disruption were identified as important constraints on farmers' ability to implement extension recommendations (Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024). Livelihood shocks, including food insecurity, income instability, labor scarcity, migration pressure, health shocks, asset depletion, and gendered vulnerability, were often treated as outcomes or background conditions rather than as independent shock domains (Ado et al., 2019; Mohammed et al., 2021; Murray et al., 2016; Ngigi et al., 2021). Evidence on compound and cascading shocks remained limited, even though several studies showed that climate, market, financial, and livelihood pressures often interact, with drought or supply-chain disruption translating into yield loss, food insecurity, debt, income decline, and livelihood stress (Davis et al., 2021; Michalscheck et al., 2023; Panja et al., 2026). Overall, the literature remains strongly climate-centered, while market, livelihood, and compound shocks are underdeveloped despite their central role in shaping smallholder resilience.

**Table 3.** Shock domains addressed in the included literature.

| Shock domain | Main issues identified | Extension-related response | Main resilience outcome | Representative studies |
|---|---|---|---|---|
| Climate shocks | Drought, rainfall variability, floods, heat stress, pests, water stress, crop failure, soil degradation. | Climate-smart agriculture training, climate information services, farmer field schools, farmer extension facilitators, weather advisories. | Adaptive practice change, reduced production risk, improved preparedness. | (Abegunde et al., 2019; Acevedo et al., 2020; Nkiaka et al., 2019; Pienaah & Luginaah, 2024; Wekesa et al., 2018) |
| Market shocks | Input-price increases, output-price instability, weak bargaining power, market-access barriers, postharvest losses, value-chain disruption. | Market-oriented extension, value-chain support, price information, financial advisory, credit and insurance linkage. | Income stability, market adaptive capacity, improved bargaining, reduced economic vulnerability. | (Davis et al., 2021; Goodwin et al., 2022; Kuhl, 2018; Lutta et al., 2024) |
| Livelihood shocks | Food insecurity, income loss, labor scarcity, migration pressure, health shocks, asset depletion, gendered vulnerability. | Livelihood advisory support, diversification training, inclusive extension, farmer learning, financial and social-protection linkage. | Livelihood diversification, food security, reduced vulnerability, stronger household coping capacity. | (Ado et al., 2019; Mohammed et al., 2021; Murray et al., 2016; Ngigi et al., 2021) |
| Compound and cascading shocks | Interacting climate, market, and livelihood pressures; climate shocks becoming food, income, and debt crises. | Integrated advisory systems combining climate, market, financial, and livelihood support. | Cross-domain resilience, absorptive/adaptive capacity, reduced cascading vulnerability. | (Davis et al., 2021; Michalscheck et al., 2023; Panja et al., 2026) |

### *4.4. Analytical Synthesis*

The thematic evidence map linking shock type, extension modality, mechanism, resilience capacity, and outcome is provided in Supplementary Table S5.

#### 4.4.1. Extension Interventions and Delivery Systems

The included studies depict agricultural extension as a pluralistic advisory system rather than a single public service. Extension was delivered through public agencies, community facilitators, farmer field schools, farmer-to-farmer learning, digital platforms, climate information services, value-chain actors, and gender-responsive advisory services. The modalities varied in purpose: some focused on promoting climate-smart practices, whereas others addressed climate-risk communication, market access, financial inclusion and livelihood diversification (Table 4).

**Table 4**. Extension interventions and delivery systems for smallholder resilience.

| Subtheme | Indicator | Role in smallholder resilience | Sources |
|---|---|---|---|
| Public and community extension | Government extension, local agents, and community facilitators | Provides local advisory support and connects farmers to public programs and technical knowledge. | (Amadu, 2022; Pienaah & Luginaah, 2024; Silici et al., 2021; Staub & Clarkson, 2021) |
| Farmer field schools and participatory learning | Group learning, demonstration, experimentation, and collective problem-solving | Builds practical knowledge, peer confidence, and local experimentation capacity. | (Kalidou et al., 2024; Pienaah & Luginaah, 2024; Silici et al., 2021; Tambo & Wünscher, 2017) |
| Farmer-to-farmer extension | Lead farmers, farmer facilitators, and horizontal knowledge diffusion | Expands advisory reach and increases trust through peer-based learning. | (Amadu, 2022; Staub & Clarkson, 2021; Tambo & Wünscher, 2017) |
| Climate information and weather advisory services | Forecasts, early warning, weather advisories, and climate-risk communication | Supports anticipatory farm decisions and preparedness under climate variability. | (Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Tamru et al., 2025; Warner et al., 2022) |
| Digital agro-advisory tools | Mobile platforms, ICT-based advice, digital extension, and data-enabled recommendations | Increases scale and speed of advisory delivery but depends on connectivity and digital literacy. | (Haworth et al., 2018; Njuguna et al., 2025; Ofosu et al., 2025; Porciello et al., 2022; Singh et al., 2025) |
| Climate-smart agriculture training | Improved seeds, soil management, water management, and conservation agriculture | Promotes adaptive practices that reduce climate-related production risk. | (Abegunde et al., 2019; Descheemaeker et al., 2016; Makate et al., 2019; Thottadi & Singh, 2024; Wekesa et al., 2018) |
| Market, financial, and livelihood advisory services | Value-chain support, price information, credit, insurance, and livelihood advice | Links resilience to income stability, market participation, and financial coping capacity. | (Batung et al., 2023; Goodwin et al., 2022; Kuhl, 2018; Lutta et al., 2024; Singh et al., 2025) |
| Gender-responsive and inclusive extension | Targeted support for women, youth, poorer farmers, and marginalized groups | Improves equity in access to knowledge, resources, and decision-making. | (Azzarri & Nico, 2022; Cavatassi et al., 2025; Murray et al., 2016; Saran et al., 2024) |

The reviewed studies commonly associated extension with resilience when technical advice, learning, trust, resource access, and institutional linkages were combined. Farmer field schools and farmer-to-farmer models were frequently reported as useful where formal systems were weak, while digital tools were associated with wider advisory reach but could exclude farmers lacking connectivity, literacy, or access to a phone. The evidence thus indicates a pluralistic model, as opposed to a single-channel model, for resilient extension.

#### 4.4.2. Resilience-Building Mechanisms

The analysis identified several mechanisms through which extension is linked to resilience. These mechanisms are risk awareness, knowledge translation, adaptive practice change, social learning, access to services, market linkage, institutional brokerage, and empowerment. Extension was most often linked to resilience when it helped farmers understand risks, experiment with practices, access services, and make decisions under uncertainty (Table 5).

**Table 5.** Reported resilience-building mechanisms associated with agricultural extension.

| Subtheme | Indicator | Role in smallholder resilience | Sources |
|---|---|---|---|
| Risk awareness and anticipation | Awareness of climate, market, and livelihood risks | Enables earlier preparation and more informed seasonal decisions. | (Cooper et al., 2008; Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Staub & Clarkson, 2021; Warner et al., 2022) |
| Knowledge translation | Practical use of scientific, climate, technical, and market information | Converts information into farm-level and livelihood decisions. | (Kalidou et al., 2024; Lipper et al., 2022; Mapfumo et al., 2016; Silici et al., 2021) |
| Adaptive practice change | Adjustment of crops, water use, soil management, livestock, and livelihoods | Supports practical adaptation under changing climate and market conditions. | (Antwi & Antwi-Agyei, 2023; Jena et al., 2023; Makate et al., 2019; Vernooy, 2022; Wekesa et al., 2018) |
| Social learning and peer diffusion | Group learning, demonstrations, networks, and farmer exchange | Builds trust, experimentation, and wider diffusion of resilient practices. | (Amadu, 2022; Koczberski et al., 2018; Pienaah & Luginaah, 2024; Staub & Clarkson, 2021; Tambo & Wünscher, 2017) |
| Access to inputs, finance, and services | Linkage to seeds, fertilizer, credit, insurance, irrigation, and public support | Enables farmers to act on extension advice rather than only receive information. | (Acevedo et al., 2020; Batung et al., 2023; Goodwin et al., 2022; Kansiime & Mastenbroek, 2016; Wekesa et al., 2018) |
| Market linkage and bargaining capacity | Access to buyers, price information, value chains, and postharvest systems | Strengthens income stability and market adaptive capacity. | (Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024; Mekonnen et al., 2024; Singh et al., 2025) |
| Institutional brokerage and trust | Linkage to institutions, farmer organizations, climate-service providers, and advisory systems | Improves coordination and credibility of resilience support. | (Azzarri & Nico, 2022; Cavatassi et al., 2025; Lidder et al., 2025; Saran et al., 2024; Warner et al., 2022) |
| Empowerment and inclusion | Agency, participation, collective voice, and decision-making capacity | Strengthens the capacity of marginalized farmers to participate in resilience pathways. | (Azzarri & Nico, 2022; Cavatassi et al., 2025; Lidder et al., 2025; Saran et al., 2024; T. G. Williams et al., 2020) |

These findings explain why extension should be understood as resilient infrastructure rather than as simple information transfer. Information supports resilience only when farmers can trust it, understand it, and access the material and institutional resources needed to act on it. The evidence was most consistently reported for knowledge translation and adaptive practice change, whereas institutional brokerage, empowerment, and market linkages were less frequently examined.

#### 4.4.3. Resilience Capacities

The reviewed evidence was organized according to three overarching resilience capacities: absorptive, adaptive, and transformative. Adaptive capacity was the most frequently identified and included farm-level, livelihood, and market-related adjustments, such as climate-smart agriculture, crop and livelihood diversification, water management, market access, and farmer learning. Absorptive capacity included early warning, preparedness, financial coping, savings, food reserves, and short-term decision-making. Transformative capacity was less frequently measured and included institutional reform, empowerment, inclusive markets, farmer organizations, and long-term innovation. Collective action and group learning were treated as cross-cutting mechanisms that could support both adaptive and transformative capacities (Table 6).

**Table 6**. Resilience capacities supported by agricultural extension.

| Subtheme | Indicator | Role in smallholder resilience | Sources |
|---|---|---|---|
| Absorptive capacity | Preparedness, early warning, savings, food reserves, and short-term coping | Helps households withstand shocks without immediate livelihood collapse. | (Abid et al., 2020; Cooper et al., 2008; Michalscheck et al., 2023; Tamru et al., 2025) |
| Adaptive capacity: farm-level adaptation | Crop diversification, improved seeds, soil management, water management, and climate-smart practices | Enables adjustment of production systems under climate stress. | (Acevedo et al., 2020; Descheemaeker et al., 2016; Jena et al., 2023; Petersen-Rockney et al., 2021; Vernooy, 2022) |
| Adaptive capacity: livelihood adaptation | Livelihood diversification, mixed farming, livestock adjustment, and nonfarm income | Reduces dependence on one crop, income source, or production system. | (Ado et al., 2019; Antwi & Antwi-Agyei, 2023; McCord et al., 2015; Mohammed et al., 2021; Ngigi et al., 2021) |
| Adaptive capacity: market adaptation | Price information, value-chain participation, input access, and market adjustment | Helps farmers respond to market volatility and stabilize income. | (Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024; Singh et al., 2025) |
| Adaptive and transformative capacities: collective action | Farmer organizations, group learning, cooperatives, and collective action | Builds shared learning, bargaining power, institutional participation, and coordinated adaptation. | (Kalidou et al., 2024; Koczberski et al., 2018; Pienaah & Luginaah, 2024; Staub & Clarkson, 2021; Tambo & Wünscher, 2017) |
| Transformative capacity | Institutional reform, gender empowerment, inclusive markets, and long-term innovation | Addresses structural conditions that reproduce smallholder vulnerability. | (Lidder et al., 2025; Mekonnen et al., 2024; Njuguna et al., 2025; T. G. Williams et al., 2020) |

Evidence linking extension to resilience was most consistently reported for adaptive capacity, including farm-level, livelihood, and market adaptation, whereas transformative capacity was less frequently examined. While many studies document the adoption of new technologies after extension contact, less research has investigated how extension influences underlying structural factors such as unequal market power, differential access to resources, poor institutions, and chronic livelihood insecurity. This restricts the extent of transformative claims that can be made on the basis of the current evidence base.

4.4.4. Farming and Livelihood Outcomes

The outcomes measured in the included studies were adoption and productivity, food security, income stability, livelihood diversification, reduced vulnerability, and resilience. The adoption of adaptive practices was the most common outcome, especially in climate-smart agriculture studies. However, resilience was not always evident through adoption. Extension was found to be associated with better food security, income stability, reduced production risk, diversified livelihoods and multidimensional resilience indicators (Table 7).

**Table 7**. Farming and livelihood outcomes associated with extension.

| Subtheme | Indicator | Role in smallholder resilience | Sources |
|---|---|---|---|
| Adoption of adaptive practices | Use of climate-smart, conservation, agroecological, digital, or risk-reducing practices | Indicates immediate behavioral response to extension, although not always durable resilience. | (Acevedo et al., 2020; Jena et al., 2023; Makate et al., 2019; Tamru et al., 2025; Thottadi & Singh, 2024) |
| Production and risk reduction | Productivity, reduced crop loss, lower production risk, and stable farm performance | Shows whether extension improves farming outcomes under stress. | (Jena et al., 2023; Tamru et al., 2025; Thottadi & Singh, 2024; Wekesa et al., 2018) |
| Food security | Food availability, access, utilization, and stability | Links extension to household welfare rather than only farm practice. | (Ado et al., 2019; Kalidou et al., 2024; Koczberski et al., 2018; Mohammed et al., 2021; Wekesa et al., 2018) |
| Income and livelihood stability | Income security, poverty reduction, and diversified income sources | Demonstrates whether advisory support strengthens livelihood resilience. | (Ado et al., 2019; Batung et al., 2023; Jena et al., 2023; McCord et al., 2015; Ngigi et al., 2021) |
| Reduced vulnerability | Lower sensitivity, stronger coping capacity, and improved recovery | Captures resilience beyond adoption and production indicators. | (Endalew & Sen, 2020; Ramilan et al., 2022; P. A. Williams et al., 2018; T. G. Williams et al., 2020) |
| Resilience measurement outcomes | Resilience indices, vulnerability measures, adaptive-capacity scores, and livelihood-resilience indicators | Provides a multidimensional assessment of resilience but varies across studies. | (Douxchamps et al., 2017; Holland et al., 2017; Michalscheck et al., 2023; Ramilan et al., 2022; P. A. Williams et al., 2018) |

The evidence base still relies heavily on adoption as a proxy for resilience. This is analytically weak, as adoption does not necessarily imply a reduction in vulnerability or enhanced recovery and livelihood security. Future research should examine whether adopted practices produce long-term resilience outcomes, rather than measuring adoption alone.

#### 4.4.5. Equity and Contextual Moderators

Equity and context strongly shape whether extension translates into resilience. Farmers' access to, understanding of, and implementation of advisory services are affected by gender, land access, asset ownership, digital literacy, institutional trust, agroecological context, and market access. The studies indicated that extension can be a means of reducing vulnerability if it reaches out to marginalized farmers, but it can also be a means of reproducing inequality if more resourced farmers are able to access and utilize advisory services (Table 8).

**Table 8**. Equity and contextual moderators of extension-resilience pathways.

| Subtheme | Indicator | Role in smallholder resilience | Sources |
|---|---|---|---|
| Gendered access to extension | Gender differences in information, land, labor, credit, and decision-making | Shapes who benefit from advisory services and who remains excluded. | (Azzarri & Nico, 2022; Cavatassi et al., 2025; Murray et al., 2016; Saran et al., 2024) |
| Wealth, land, and asset inequality | Farm size, assets, education, and resource access | Determines whether farmers can act on extension recommendations. | (Aschinger et al., 2023; Holland et al., 2017; Ramilan et al., 2022; T. G. Williams et al., 2020) |
| Digital access and literacy | Connectivity, phone ownership, digital literacy, language, and trust | Conditions the effectiveness and inclusiveness of digital advisory systems. | (Haworth et al., 2018; Njuguna et al., 2025; Ofosu et al., 2025; Porciello et al., 2022) |
| Institutional trust and advisory quality | Timeliness, credibility, local relevance, and actionability of advice | Determines whether farmers use extension information in decision-making. | (Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Ofosu-Ampong et al., 2025; Warner et al., 2022) |
| Agroecological and market context | Local ecology, infrastructure, farming system, and market access | Conditions under which extension strategies are feasible and effective. | (Descheemaeker et al., 2016; Holland et al., 2017; Lutta et al., 2024; McCord et al., 2015; Petersen-Rockney et al., 2021; Warner et al., 2022) |

The key question here is that we should not take for granted the fact that extension is equally beneficial for all farmers. Advisory services might be more beneficial to farmers with better land, assets, education, connectivity, or market access than to poorer or marginalized farmers. This finding supports the need for gender-sensitive, resource-sensitive, and context-specific extension systems.

4.4.6. Evidence Gaps and Methodological Limitations

The last theme identified the key gaps in the current evidence base. The literature still focuses on climate adaptation, and relatively less attention has been given to market shocks, livelihood shocks and compound risks. Adoption, participation, or awareness are often used as proxies for resilience in many studies. Longitudinal and causal evidence remains scarce, and transformative capacity is often assumed rather than directly measured (Table 9).

**Table 9.** Evidence gaps and methodological limitations in the extension-resilience literature.

| Subtheme | Indicator | Implication for the evidence base | Sources |
|---|---|---|---|
| Climate-adaptation bias | Dominance of climate-smart agriculture and adaptation studies | Understates the role of market and livelihood shocks in smallholder resilience. | (Acevedo et al., 2020; Davis et al., 2021; P. A. Williams et al., 2018) |
| Weak compound-shock analysis | Limited analysis of interacting climate, market, and livelihood shocks | Reduces understanding of how farmers experience overlapping risks. | (Davis et al., 2021; Michalscheck et al., 2023; Panja et al., 2026) |
| Overuse of adoption proxies | Reliance on adoption, participation, or awareness indicators | Risks overstating resilience outcomes without measuring welfare, recovery, or vulnerability reduction. | (Acevedo et al., 2020; Silici et al., 2021; Thottadi & Singh, 2024) |
| Limited longitudinal and causal evidence | Few studies tracking extension effects over time | Weakens claims about durable resilience-building pathways. | (Douxchamps et al., 2017; Michalscheck et al., 2023; T. G. Williams et al., 2020) |
| Undermeasured transformative capacity | Limited measurement of institutional change, empowerment, market power, and structural transformation | Restricts understanding of whether extension changes deeper causes of vulnerability. | (Cavatassi et al., 2025; Kuhl, 2018; T. G. Williams et al., 2020) |
| Limited equity-disaggregated evidence | Weak disaggregation by gender, wealth, age, location, and social position | Makes it difficult to assess who benefits from extension and who is excluded. | (Azzarri & Nico, 2022; Cavatassi et al., 2025; T. G. Williams et al., 2020) |

While there is strong evidence in the literature of the ability of extension to support adaptive practice change, there is less evidence of the ability to create durable, inclusive, and transformative resilience. Future research should therefore shift from adoption-centered studies to mechanism-based, long-term, equity-sensitive, and compound-shock analyses of agricultural extension.

## 5. Discussion

### *5.1. Main Synthesis*

This scoping review shows that agricultural extension supports resilient smallholder farming systems through several interconnected pathways rather than a single intervention logic. Across the 58 included studies, extension was most commonly associated with resilience through knowledge provision, climate-risk communication, farmer learning, access to inputs and services, market linkages, institutional brokerage, and empowerment. These mechanisms varied across climate, market, livelihood, and compound-shock contexts. Climate information services and weather advisories enable anticipatory decision-making; farmer field schools and farmer-to-farmer extension facilitate social learning and experimentation at the local level; market-oriented and financial advisory services help to gain access to value chains, credit and insurance; and inclusive extension approaches help determine who could access and use resilience support (Amadu, 2022; Kuhl, 2018; Nkiaka et al., 2019; Pienaah et al., 2024; Porciello et al., 2022).

The core conclusion is thus that extension facilitates resilience through the provision of information that helps farmers understand risk, mobilize resources, make adjustments, and coordinate responses in the face of uncertainty. This finding aligns with the literature on smallholder adaptation, which highlights the importance of knowledge systems, institutions, markets, assets, and social relations in addition to technical practices for resilience (Acevedo et al., 2020; Davis et al., 2021; P. A. Williams et al., 2018). The review also revealed that there is an uneven evidence base. The most substantiated evidence is on adaptive capacity and climate-smart practice change; the least substantiated evidence is on market shocks, livelihood shocks, compound risks, transformative capacity, and equity-disaggregated outcomes.

### *5.2. Moving Beyond Technology Adoption*

One of the key takeaways from this review is that extension research needs to shift away from technology adoption, which is the most common measure of resilience. Several studies have focused on the adoption of CSA, improved varieties, soil and water conservation, crop diversification, and other adaptation practices by farmers. While these are important outcomes, they are not necessarily indicators of resilience. Adoption does not necessarily translate into reduced vulnerability, improved food security, better shock recovery, and/or structural livelihood change (Acevedo et al., 2020; Silici et al., 2021; Thottadi & Singh, 2024). From a livelihood-diversification perspective, this distinction is important. Farmers may adopt a promoted practice but remain vulnerable if they lack credit, irrigation, storage, labor, secure markets, insurance, social protection, or decision-making power. Conversely, resilience may be built through mixed farming, livestock adjustment, off-farm income, savings, market participation, social networks, and diversified livelihood strategies, even when adoption of a single promoted technology remains limited. Extension should therefore be evaluated through a broader capability lens: whether farmers are better able to absorb shocks, adapt livelihoods, stabilize income, protect food security, and avoid erosive coping.

Resilience requires a broader range of capacities. Farmers must be equipped with timely information, confidence in making decisions, financial resources, market access, social protection, institutional support, and the capacity to adapt to new climates and economic realities. Climate-smart agriculture training, for example, may increase knowledge and awareness, but farmers may still be unable to implement recommended practices if they lack credit, irrigation, quality inputs, storage capacity, or market access. Likewise, digital advisory messages are not always locally relevant, trusted, or actionable to improve resilience. This is important, as resilience is not a single practice but rather a capacity to manage uncertainty in multiple spheres of farm, household, market, and institutional life (Davis et al., 2021; Kuhl, 2018; Michalscheck et al., 2023).

In this way, the study suggests a shift from an adoption-based approach to a capability-oriented approach to extension. In this model, extension is measured not only by the actual rate of adoption of a technology promoted by extension but also by the capacity of the farmers to absorb, adapt, and transform. This is necessary to develop a more realistic view of the role of extension in resilient smallholder farming systems.

### *5.3. Extension as Resilient Infrastructure*

Conceptually, this review frames agricultural extension as ‘resilient infrastructure.” This is not to say that extension is just a means of communication for technical information. Instead, extension is understood as a social and institutional system that helps farmers make sense of risk, mobilize resources, coordinate responses, learn collectively, and reorganize livelihoods after shocks. Extension systems, such as physical infrastructure, influence the resilience of rural communities to stress; however, extension systems influence them through knowledge, relationships, trust, institutions, and collective learning.

This framing is useful for understanding why pluralistic extension systems are relevant in shock-prone smallholder scenarios. Extension services, farmer groups, cooperatives, NGOs, private organisations, climate service providers and digital platforms all offer a variety of support. There is no single actor that can answer the entire spectrum of climate, market and livelihood risks. Farmer field schools and farmer-to-farmer approaches can enhance experimentation and farmer-to-farmer learning; climate information services can increase preparedness; market-oriented extensions can help farmers connect with value chains; financial advisory services can help farmers cope and invest; and inclusive extension approaches can reduce inequities in access to knowledge and resources (Amadu, 2022; Nkiaka et al., 2019; Pienaah et al., 2024; Staub & Clarkson, 2021).

Framing extension as resilient infrastructure also highlights the importance of advisory quality. Extension can only become resilience-enabling if it is credible, locally relevant, timely, inclusive and linked to material resources. Advice alone, without inputs, credit, markets or social support, can increase awareness without fostering resilience. In contrast, good extension can serve as a link between farmers and other systems that determine their ability to act on shocks.

### *5.4. Climate Bias in the Evidence Base*

The evidence base is strongly climate-focused. The most common drought-, rainfall variability-, heat stress-, flood-, water stress-, crop failure-, pest pressure-, and climate-smart agriculture-related studies are highlighted. This focus is understandable, as climate change is a serious threat to smallholder farming systems, and many interventions have been geared toward adaptation and climate-smart agriculture (Abegunde et al., 2019; Acevedo et al., 2020; Wekesa et al., 2018). The review, however, indicates that the impacts of market shocks and livelihood shocks are underrepresented in the systematic attention given to the various shocks that may affect farmers' ability to act on climate advice.

This climate bias poses a significant analytical constraint. Climate shocks are not usually the only factor that creates vulnerability for smallholders. Climate stress frequently translates into livelihood insecurity through the loss of yields, rising food prices, pressure on inputs, debt, a shortage of labor, and unreliable market access. Similarly, market volatility can have a negative effect on the sustainability of climate-responsive agriculture by decreasing farmers' ability to afford farm inputs, store their production, bargain with market prices, or invest in adaptation. Research on food-system shocks, market systems and value-chain resilience indicates that resilience requires interaction between the ecological and economic systems, not just adaptation at the farm level (Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024).

The central implication is that extension research should examine the interconnections among climate, market, and livelihood shocks. Climate-smart extensions are important but not enough when they are not linked to price information, credit, insurance, input systems, postharvest support, social protection, or livelihood diversification. Future advisory services should therefore integrate climate, market, financial, and livelihood support.

### *5.5. Digital Extension: Opportunity and Risk*

Digital extension appears to be a promising but uneven pathway for strengthening smallholder resilience. Using digital advisory tools can help scale, speed, and personalize agricultural advice. The use of mobile platforms, weather alerts, digital market information, and data-driven recommendations could provide farmers with timely information, particularly in regions where traditional extension services are lacking, thus supporting decision-making. Compared with traditional face-to-face extension, digital systems are especially relevant with respect to climate-risk communication, as they can provide faster and more efficient seasonal forecasts, weather warnings, and early warnings.

However, the review also shows that digital extension is neither inherently inclusive nor a stand-alone solution for resilience. Digital advisory platforms may fail to reach farmers who are less literate, less connected, have fewer smartphones, struggle with language, lack trust in digital platforms, or lack the capacity to respond to advice. This is particularly true for women farmers, less well-off families, older farmers, and remote communities. Therefore, digital extension may exacerbate existing inequalities if it is used as a substitute for human facilitation rather than as a complement to locally grounded advisory services (Azzarri & Nico, 2022; Ofosu-Ampong et al., 2025; Porciello et al., 2022).

A key policy lesson is that digital extension should be coupled with human intermediation. Digital information can be translated into locally relevant and actionable advice through the support of community facilitators, farmer groups, local extension agents, and peer groups. A blended model is more likely than a purely platform-based model to support resilience, particularly where trust, interpretation, and access to resources remain major challenges.

### *5.6. Gender and Social Inclusion*

The review emphasizes the need to move from gender-sensitive extension toward gender-transformative extension. Gender-sensitive extension takes into account that women and men have different needs, constraints, and access to extension. Gender-transformative extension, however, is concerned with structural conditions and power dynamics that produce unequal resilience, such as unequal land access, limited mobility, unequal care responsibilities, unequal access to credit, unequal control over income, unequal participation in farmer groups, and unequal access to digital tools and formal farmer advisory services (Azzarri & Nico, 2022; Cavatassi et al., 2025; Murray et al., 2016).

This distinction matters, as extension has the potential to either diminish or magnify inequality. Advisory services may be unintentionally gender biased by aiming for household heads, land owners, smartphone users, or more market-connected farmers. In such cases, extension may increase average adoption while widening inequalities in resilience. Inclusive extension, on the other hand, has the potential to increase resilience by helping women gain access to knowledge, inputs, markets, organizations and decision-making spaces.

Social inclusion should therefore be treated as a core resilience criterion rather than as an additional project objective. Gender, wealth, age, landholding, location and digital access disaggregation of resilience outcomes are needed. In the absence of disaggregation, it is not possible to identify who is more resilient and who is still vulnerable. A first-class research program on extension and resilience therefore needs to consider distributional effects, as well as aggregate effects.

### *5.7. Toward a Mechanism-based Research Agenda*

Future studies should prioritize mechanism-based research. While many studies report links between extension participation and adoption, awareness, or adaptive capacity, fewer explain how, under which conditions, and for which farmers extension supports resilience. A mechanism-based agenda would require studies to specify the type of extension, the expected resilience mechanism, the shock context, the resilience capacity measured, the target population, and the time horizon of effects.

This would enhance the theory and evidence. For example, climate information services may build absorptive capacity through anticipatory decision-making; farmer field schools may support social learning and experimentation; market-oriented extension may strengthen bargaining capacity and value-chain linkages; and gender-responsive extension may support empowerment and resource access. These are distinct systems and should not be used interchangeably. Similarly, there are indicators and time frames for absorptive, adaptive, and transformative capacities. Early warning could have a more facilitating role in short-term coping, and farmer organizations, market access, and gender empowerment could be more relevant in longer-term transformation.

Future studies should thus seek to answer six questions: what kind of extension is provided? How does it hope to foster resilience? What shocking situation does it cover? Which resilience capacity is being measured? Who benefits from improved resilience? Are consequences short-term, adaptive, or transformative? The answers to these questions would help to take the field beyond general statements of extension or resilience to more specific, cumulative, and policy-relevant evidence.

### *5.8. Policy Implications*

The results have several implications for agricultural extension policy and program design. First, governments and development partners need to further develop pluralistic extension systems, which involve public extension, farmer organizations, NGOs, cooperatives, private actors, climate-service providers, and digital platforms. Resilience needs coordinated support, knowledge, markets, finance, and institutions—it is not something that can be delivered via a single advisory channel.

Second, there is a need for extension systems to include climate, market, and livelihood advisory services. Farmers should be informed about the availability of inputs, prices, storage, and credit; rains, pests, and agronomic practices; and markets and livelihood opportunities. This integration is particularly relevant during compound shocks, i.e., climatic stress, economic insecurity, and household vulnerability.

Third, investment in farmer field schools, farmer-to-farmer learning, and participatory innovation is important. These models enable trust, local experimentation, peer diffusion, and collective problem solving. They are especially useful in situations where the formal extension system is constrained in staffing and where localized knowledge rather than general knowledge is needed.

Fourth, last-mile climate information should be improved. Climate advisories need to be timely, location-specific, understandable, and actionable. Information needs should be connected to practical considerations, such as planting decisions, crop choice, water management, and pest response, as well as livelihood planning. Forecasts become more useful for resilience only when farmers can understand and act on them.

Fifth, extension should be coupled with credit, insurance, markets, and social protection. Adaptation recommendations that ignore financial and institutional barriers may shift responsibility to farmers without enabling them to adapt. Extension services should be combined with financial and market support to strengthen adaptive and absorptive capacities.

Sixth, extension needs to be gender-responsive, youth-inclusive, and sensitive to social inequalities. Extension programmes need to address barriers related to land access, mobility, unpaid care work, digital exclusion, credit, and participation in farmer groups. Inclusion should be assessed through substantive and distributional outcomes rather than participation numbers alone.

Finally, digital extension should be embedded within a blended advisory system. Digital tools can increase reach and speed; however, they need to be supplemented with facilitation, local organizations, and feedback systems. Strengthening local extension capacity for compound shocks requires not only better technologies but also stronger institutions, trusted intermediaries, and advisory systems that connect climate, market, and livelihood resilience.

## 6. Conclusion

This scoping review mapped evidence from 58 studies on how agricultural extension supports resilient smallholder farming systems under climate, market, livelihood, and compound shocks. The findings show that extension is linked to resilience through risk awareness, knowledge translation, social learning, access to inputs and services, market linkages, institutional brokerage, and empowerment. These pathways mainly support adaptive capacity, while evidence on absorptive and transformative capacities remains less developed.

The evidence base is strongest for climate adaptation, climate-smart agriculture, farmer learning, and adaptive practice change. Extension approaches such as farmer field schools, farmer-to-farmer learning, climate information services, digital advisory tools, and climate-smart agriculture training were commonly associated with improved decision-making and adaptive farm practices under climatic stress. However, market shocks, livelihood shocks, and compound risks remain less systematically examined, despite their importance in shaping smallholder vulnerability. Many studies also continue to use adoption, awareness, or participation as proxies for resilience, without sufficiently assessing food security, income stability, recovery capacity, vulnerability reduction, or long-term transformation.

Conceptually, this review frames agricultural extension as a resilient infrastructure: a social and institutional system that connects farmers with knowledge, resources, markets, institutions, and collective learning processes. This framing moves beyond the traditional view of extension as technology transfer and highlights the need for locally relevant, timely, inclusive, and resource-linked advisory systems. Digital extension can improve scale and speed, but it should complement rather than replace human facilitation, particularly where connectivity, literacy, language, trust, and gendered access remain unequal.

For policy and practice, extension systems should be pluralistic, inclusive, market-aware, and shock-responsive. Climate advisory services should be integrated with market information, credit, insurance, input access, social protection, livelihood diversification, and farmer-organization support. Gender-responsive and youth-inclusive extension should also move beyond participation targets to address structural barriers that shape unequal resilience outcomes.

This review has limitations. It included only English-language studies, relied mainly on peer-reviewed literature, and did not estimate pooled intervention effects. Future research should move from adoption-centered analysis toward mechanism-based, longitudinal, and equity-sensitive studies that examine which extension pathways work, under which shock conditions, for whom, and with what absorptive, adaptive, or transformative outcomes. Such evidence is essential for designing agricultural extension systems capable of supporting smallholder farmers under growing climate, market, and livelihood uncertainty.

**Supplementary Materials:** The following supporting information can be downloaded at: https://sccpress.com/ars/libraryFiles/downloadPublic/7. Table S1: Database-specific search strategy and supplementary search notes; Table S2: Data-charting and extraction form; Table S3: Characteristics of the 58 included studies; Table S4: Term sheet for thematic analysis of agricultural extension and smallholder resilience; Table S5: Thematic evidence map of extension-resilience pathways; Table S6: Methodological and relevance appraisal framework.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CSA | Climate-smart agriculture |
| CIS | Climate information services |
| ICT | Information and communication technology |
| LMICs | Low- and middle-income countries |

| | |
|---|---|
| NGOs | Non-governmental organizations |

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Agricultural & Rural Studies

*Review*

# Financial Inclusion for Agriculture and Rural Communities: A Bibliometric Analysis and Future Directions

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**Abstract:** Despite the growing importance of financial inclusion for agricultural and rural development, the literature lacks a dedicated bibliometric synthesis of research in rural and agricultural contexts. Addressing this gap, this study provides a comprehensive bibliometric mapping of financial inclusion research in agriculture and rural areas. Using a PRISMA protocol for article identification and screening, we analyzed 197 Scopus-indexed articles (2000–2025) with VOSviewer through keyword co-occurrence analysis and thematic clustering. This approach enables us to map the field's intellectual structure, identify five major research themes, and trace its evolution from a focus on traditional financial access to broader concerns with digital finance, entrepreneurship, gender equality, and sustainable rural development. Its main contribution lies in mapping the intellectual structure and evolution of financial inclusion in agriculture and rural areas, while identifying key research gaps and a future research agenda. Drawing on the thematic clusters identified in the bibliometric analysis, the study highlights policy priorities for improving the quality and effective use of financial services, developing context-specific financial products for agriculture and rural populations, investing in digital and institutional infrastructure, and promoting gender-responsive financial inclusion.

**Keywords:** financial inclusion; agriculture; rural; bibliometric analysis; PRISMA; VOSviewer

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## 1. Introduction

Financial inclusion has become a policy priority for governments and international organizations because of its economic and social importance (Neaime & Gaysset, 2018; Sarma & Pais, 2011). Since 2011, transaction account ownership and digital payment adoption have increased substantially. However, improved access has not always translated into active use or high-quality financial services. This gap is particularly evident in rural areas, where geographic isolation, limited connectivity, and seasonal income volatility continue to constrain financial inclusion (Demirgüç-Kunt et al., 2022). Within this context, digital transformation and smart technologies have emerged as important solutions, changing how financial services are produced and used. The COVID-19 pandemic further accelerated this trend by increasing the adoption of contactless and remote financial services, and it also exposed inequalities related to connectivity, digital literacy, documentation, and trust. Rural households face additional challenges, such as strict identity and address verification, costly and unreliable cash-in/cash-out infrastructure, limited local competition, and greater vulnerability to climate and commodity-price shocks. These issues represent a persistent "last-mile" problem that urban-centric solutions inadequately addressed.

The importance of financial inclusion in policy increased after the 2007–2008 global financial crisis, when the World Bank and the International Monetary Fund framed it as a pillar of sustainable growth and poverty reduction (World Bank, 2015). In October 2013, the World Bank launched the Universal Financial Access 2020 initiative to enable every adult to have a transaction account by 2020 (World Bank, 2021). In 2015, financial inclusion was recognized as a key enabler of the 2030 Agenda, with explicit links to 7 of the 17 Sustainable Development Goals (United Nations Secretary-General's Special Advocate [UNSGSA], 2019). Since then, global challenges have intensified due to the COVID-19 pandemic and the Russia–Ukraine conflict. According to World Bank estimates, these crises pushed about 97 million additional people into extreme poverty in 2021, while around 163 million people lived on less than $5.50 per day (Sánchez-Páramo et al., 2021). Against this backdrop, financial inclusion has become increasingly important for supporting households and businesses, reducing poverty, and promoting inclusive economic growth.

Extensive academic research has examined the complex nature of financial inclusion using diverse theoretical lenses and empirical designs. This research shows that financial exclusion, especially among vulnerable groups, reduces savings, leads to inefficient credit allocation, and weakens risk management for households and businesses, ultimately hindering sustainable growth (Neaime & Gaysset, 2018; Sarma & Pais, 2011). With the continued growth of the literature, bibliometric techniques, including co-word analysis, co-citation analysis, and science mapping using VOSviewer, together with systematic reviews, have become valuable tools for organizing and synthesizing the evidence (Ahiase et al., 2024; Gallego-Losada et al., 2023).

Recent bibliometric mappings have advanced our understanding of the field but leave a specific gap that this study seeks to fill. Ahiase et al. (2024) and Gallego-Losada et al. (2023) map digital financial inclusion across all sectors, while Ghosh (2024) traces general financial inclusion trends around initiation, service delivery, and customer-centric design. Mushtaq et al. (2023) synthesize women-focused financial inclusion, and Khan et al. (2022) review the role of financial literacy. None of these reviews specifically examines rural and agricultural financial inclusion as a distinct research domain. Consequently, research themes shaped by the unique characteristics of rural livelihoods—such as seasonal cash flows, integrated savings-credit-insurance services, limited cash-in/cash-out infrastructure in thin markets, and climate-related vulnerabilities—remain insufficiently captured in existing bibliometric mappings. The human dimensions of financial inclusion, including gender disparities, digital trust, and household well-being, have received comparatively limited attention, despite their heightened relevance in rural and agricultural contexts.

To address this gap, the study is guided by three research questions: (RQ1): What is the intellectual structure of research on rural and agricultural financial inclusion published from 2000 to 2025, in terms of publication trends, leading countries, contributing journals, and most-cited works? (RQ2): What are the major thematic clusters in this body of literature, and how have they evolved over time? (RQ3): What research and policy priorities emerge from the identified thematic structure, particularly with respect to quality of use, provider viability, and equity in rural settings?

This research makes three specific contributions. First, this study provides a bibliometric review that examines rural and agricultural financial inclusion as a distinct research domain, highlighting themes that are often overlooked in broader financial inclusion reviews. Second, it goes beyond descriptive mapping by identifying five thematic clusters organized according to two complementary dimensions: geographic context and research focus. Each cluster is supported by representative keywords and key publications. Third, the bibliometric findings are translated into a future research agenda comprising three broad directions: enhancing the development impacts of financial inclusion, improving its responsiveness to the diverse needs of rural populations, and understanding the contextual determinants of financial inclusion outcomes. The findings also highlight four policy priorities: improving the quality and effective use of financial services, developing context-specific financial products for agriculture and rural populations, strengthening digital and institutional infrastructure, and promoting gender-responsive financial inclusion. Together, these contributions advance the conceptual understanding of rural and agricultural financial inclusion. In particular, this study highlights a dimension that has received limited attention in urban-focused financial inclusion research: the provider viability of delivering financial services in rural areas. The review shows that, although financial services may be available and adopted in rural markets, their long-term development is often constrained by provider viability in thin markets and by barriers to continued and safe use. Bringing this rural-specific perspective to the forefront offers a clearer conceptual lens for future research on financial inclusion in agricultural contexts. In addition, the findings provide practical implications by highlighting the need to tailor financial interventions to rural-specific challenges. They offer guidance for policymakers in designing targeted strategies to improve service quality, strengthen the resilience of rural households, promote inclusive growth, and support sustainable rural development.

The remainder of the paper is organized as follows. Section 2 presents the study's conceptual foundation and reviews previous bibliometric research. Section 3 describes the bibliometric methodology and applies it to map the field's evolution. Section 4 reports the findings by identifying the field's intellectual structure and major research themes. Finally, Section 5 discusses the theoretical and practical implications of the findings, outlines future research directions, and concludes with the study's limitations.

## 2. Literature Review

### *2.1. Conceptual Foundation*

Financial inclusion refers to access to and use of formal financial services by individuals and households at an adequate quality and affordability (Demirgüç-Kunt et al., 2022). It is consistently linked to poverty reduction, income equality, savings behavior, productive investment, and gender empowerment (Neaime & Gaysset, 2018; Sarma & Pais, 2011). Financial exclusion, by contrast, tends to reinforce poverty traps and inequality among vulnerable populations and disadvantaged regions.

Rural financial markets face structural conditions that make inclusion particularly challenging. Rural households are exposed to seasonal cash flows, geographical isolation, climate and commodity-price shocks, and limited documentation (Adegbite & Machethe, 2020; Bali Swain & Nsabimana, 2024). These conditions generate the high transaction costs and information asymmetries that classical work in financial economics has long recognized as core frictions in rural credit markets, within which financial institutions must operate to reach excluded populations.

Digital financial inclusion (DFI) has emerged as an important response to these barriers. By leveraging mobile technologies, digital public infrastructure, and alternative data, DFI extends financial services to remote and underserved populations at lower cost than branch-based delivery, and supports new forms of credit scoring in the absence of formal collateral and credit histories, thereby lowering, though not eliminating, the transaction-cost and information barriers characteristic of rural financial markets (Jena, 2025; L. Zhang et al., 2023). Empirical works have examined the mechanisms through which DFI influences farm productivity, entrepreneurship, and household welfare, as well as barriers to sustained use (Bongomin et al., 2023; Wang & Fu, 2022; Wang & He, 2020).

A central concept in this review is the distinction between "access" and "quality of use." Building on the three-dimensional framework of access, usage, and quality proposed in international financial inclusion research (Ardic et al., 2012), we define "access" as the ability to obtain and reach formal financial services, whereas "quality of use" refers to the extent to which these services are used effectively, consistently, and in ways that improve users' financial well-being. In this review, the latter concept encompasses both the usage and quality dimensions of the international framework, reflecting the depth and effectiveness of financial service use in rural and agricultural contexts. This distinction provides the conceptual basis for understanding the evolution of financial inclusion research from expanding access to enhancing meaningful and sustainable financial service use. Besides, unless otherwise indicated, the terms "sustainability" and "sustainable development" used in this review refer broadly to long-term development outcomes across economic, social, and environmental dimensions.

### *2.2. Previous Bibliometric Reviews*

As research on financial inclusion continues to expand, several scholars have recently adopted systematic reviews and bibliometric methods to better synthesize the growing literature. However, most of these mapping efforts focus on the broader landscape, particularly the global diffusion of digital financial services. Gallego-Losada et al. (2023) have tracked the overall growth of digital financial inclusion, while Ahiase et al. (2024) and Ghosh (2024) used tools like VOSviewer and co-word analysis to highlight how financial inclusion drives economic development and sustainability. While these reviews effectively outline general trends, they share a common limitation: they typically adopt a macro-level or predominantly urban perspective, with limited attention to sector-specific or context-specific settings.

Systematic reviews focusing specifically on agriculture and rural communities remain scarce. Farming populations face distinct challenges, such as unpredictable weather, seasonal incomes, and physical isolation, that standard urban financial access models fail to address. Most broad literature mappings overlook these on-the-ground realities. While a few recent studies have started exploring related specific cases and contexts (as shown in Table 1), they typically treat rural development as a secondary implication rather than their primary focus of analysis.

**Table 1.** Summary of Bibliometric and Systematic Literature Reviews.

| Author | Title | Key Areas | Methodology | Database coverage | Analytical tools | Contributions | Key limitations |
|---|---|---|---|---|---|---|---|
| Del Sarto & Ozili (2025) | FinTech and financial inclusion in emerging markets: a bibliometric analysis and future research agenda | Emerging markets; Innovation; Financial inclusion; Fintech. | Bibliometric analysis with performance analysis and science mapping (VOSviewer) | Scopus database; 2015-4/2024; 737 initial → 313 final papers | Bibliometric analysis; VOSviewer; Thematic map; Bibliographic coupling analysis (BcA) | FinTech significantly advances financial inclusion in emerging markets. Identifies "FinTech for rural development" as a vital future research agenda to bridge the gap between urban and rural financial services. | Long-term impacts of FinTech on financial stability remain underexplored. Specific needs of marginalized populations not fully addressed. |
| Mushtaq et al. (2023) | Women Financial Inclusion Research: A bibliometric and Network Analysis | Women; Gender disparities; Financial Inclusion; Bibliometric Analysis. | Bibliometric analysis with citation analysis, bibliographic coupling, and co-word analysis | Scopus database; Timeframe up to June 2022; 278 initial documents → 235 final documents; Articles (189), book chapters (19), conference papers (15), reviews (6) | Bibliometric analysis; VOSviewer; SPAR-4-SLR protocol | Identifies major contributors and four significant themes: the impact of microfinance on women, financially excluded segments (including rural populations), non-economic impacts, and financial literacy. | Only three basic bibliometric techniques applied (citation, coupling, co-word). Sci-MAT analysis not used to detect evolving and motor themes. |
| Khan et al. (2022) | Women Financial Inclusion Research: A bibliometric and Network Analysis | Financial literacy; Financial inclusion; Universal financial access; SDG. | Systematic Mapping Study (SMS) + SLR following PRISMA (Kitchenham 3-phase proto-col) | 5 databases: Web of Science, Scopus, DOAJ, ScienceDirect, Springer; 1975-3/2020; Quasi-gold standard search strings; 10,091 studies reviewed → 77 studies; Sample of > 850,000 individuals worldwide. | Systematic Mapping Study (SMS) + Systematic Literature Review (SLR); VOSviewer; Snowballing (backward & forward) and author search; NVIVO SQL for thematic content analysis; Kappa statistic for inter-reviewer agreement. | Synthesizes the multifaceted role of financial literacy as a determinant, moderator, mediator, and resultant in achieving financial inclusion across diverse demographics. | According to the authors, researcher bias remains at some level, gaps and future research identified are purely based on authors' views. Small final sample (77). Studies published after March 2020 are not included. |

As shown in Table 1, existing reviews are highly fragmented. They usually focus on isolated topics like FinTech adoption or financial literacy rather than inclusive finance in the overarching sense and lack a comprehensive analysis connecting inclusive finance in agriculture with the broader rural community. To bridge this gap, our study maps how these areas overlap, providing a practical taxonomy and a focused agenda for future research.

## 3. Methodology

We conducted a Scopus–based bibliometric study because Scopus is a curated abstract-and-citation database with broad global coverage and standardized metadata, widely used for large-scale research evaluation and mapping (Baas et al., 2020). We used Scopus as the sole search database for three reasons. First, Scopus covers Social Sciences and Business/Economics journals more broadly than Web of Science in the fields most relevant to our topic, including regional journals from Asia and Africa that are important for rural financial inclusion research. Second, using a single database avoids duplicate records, terminology drift, and the harmonization issues that arise when combining sources with different indexing rules. Third, Scopus applies consistent quality controls and provides the structured metadata (author affiliations, keywords, references) required for VOSviewer-based co-word and clustering analysis. We acknowledge that this choice may miss studies indexed only in Web of Science, region-specific databases, or grey literature, and we discuss this limitation in Section 5. Our objective was to chart the intellectual structure of research on financial inclusion in rural contexts from January 2000 to the end of 2025, identify key research themes and highlight gaps for future exploration.

Following the PRISMA 2020 logic (Page et al., 2021), we conducted a Scopus search in June 2026 and queried the title fields with the Boolean string: (“financial inclusion” OR “financial deepening” OR “financial equity” OR “financial access” OR “digital financial inclusion” OR “DFI” OR “financial inclusi*” OR “inclusi* financ*”) AND (“agri” OR “agricultur*” OR “rural”). The search returned 436 records. We then applied inclusion filters in two steps. In the first step, we kept only journal articles written in English and excluded all other document types such as reviews, conference papers, and book chapters, as well as records not in English. This step removed 109 records, leaving 327 records. In the second step, we limited the research fields to three subject areas (Economics, Econometrics and Finance; Business, Management and Accounting; and Social Sciences) and kept only records published between 2000 and 2025. This step removed a further 130 records, leaving 197 records for further analysis. All records were exported in CSV format. We then read the title and abstract of each remaining record to confirm relevance to financial inclusion in a rural or agricultural context. No articles were excluded at this stage. The final sample of 197 Scopus-indexed journal articles was used for the bibliometric analysis (Figure 1). The data were retrieved in June 2026, covering the period up to the end of 2025.

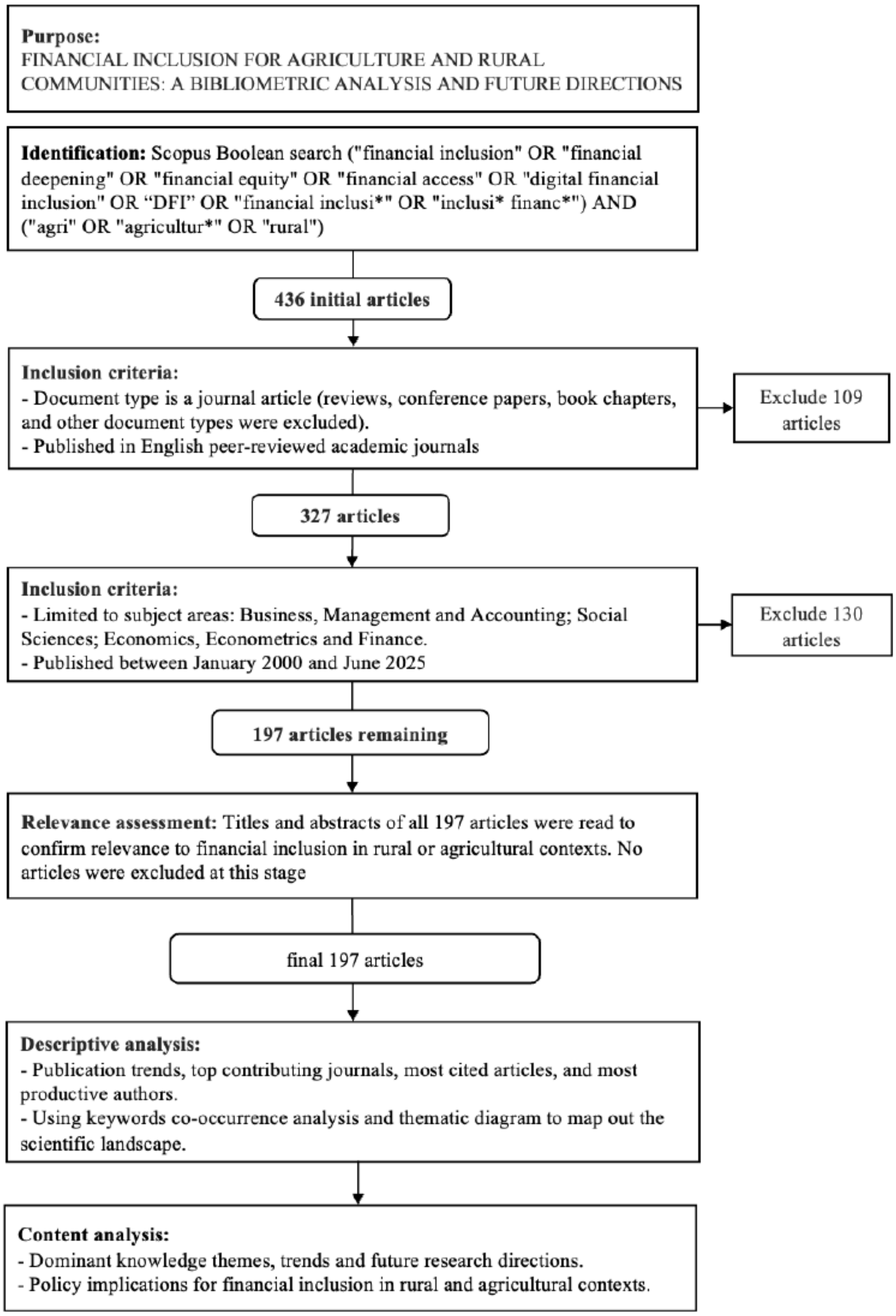


**Figure 1.** PRISMA-inspired flow diagram.

The search string was deliberately anchored on the term financial inclusion and its lexical variants rather than extended to related terms such as microfinance, rural credit, agri-finance, or rural banking. Although these concepts are closely related, they represent specific financial services, delivery mechanisms, or institutional domains rather than the broader concept of financial inclusion itself. Financial inclusion focuses on whether individuals and households can access, use, and benefit from formal financial services, whereas the adjacent literatures often examine particular financial products, institutions, or financing models. Including these terms would substantially broaden the scope of the review and introduce studies whose primary focus is financial service provision rather than financial inclusion.

To improve lexical consistency, we lower-cased text, removed stop-words and overly generic terms, and harmonized terminology with a VOSviewer thesaurus (e.g., digital inclusive finance ↔

digital financial inclusion; normalization of singular /plural and hyphenation). Bibliographic records were exported from Scopus in CSV format and, following a stepwise procedure, imported into VOSviewer v1.6.20 (van Eck & Waltman, 2010), which maps interlinkages among terms to reveal research areas based on co-occurrence patterns and conceptual associations. The software produced both network and density maps. A co-word analysis was conducted on the abstracts, author-provided keywords, indexed keywords, and abstract-derived terms. We used full counting with association strength normalization and set the minimum term occurrences to 3 (with sensitivity checks at thresholds 4 and 5). We used VOSviewer's default modularity routine (resolution = 1.00) for clustering. VOSviewer automatically grouped highly co-occurring terms into five clusters; using the highest-frequency terms and intra-cluster link structures as anchors, we assigned labels and consolidated these clusters into five overarching research themes.

## 4. Results and Discussions

### *4.1. Publication Trends*

Figure 2 reports the annual number of Scopus-indexed articles on financial inclusion from 2001 to 2025 (N = 197). The red line plots the cumulative article count. Its slope increases after the mid-2010s (the cumulative curve steepens), signaling an acceleration in yearly output from 2016 onward.

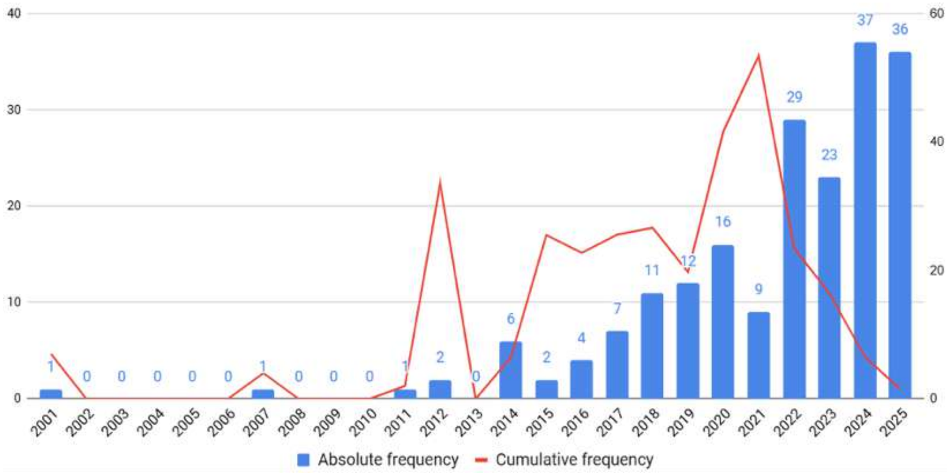


**Figure 2.** Publication trends.

In phase 1 (2001–2010), only two papers in the corpus used the term "financial inclusion" in their titles. This near-flat curve should not be read as an absence of research on rural financial issues in that decade. In practice, "financial inclusion" emerged as a prominent policy and research agenda only after the 2007–2008 global financial crisis (World Bank, 2015), and was further consolidated through subsequent milestones such as the Universal Financial Access 2020 initiative (World Bank, 2021) and its integration into the Sustainable Development Goals in 2015 (UNSGSA, 2019). Before this period, substantively related work was published under different labels such as microfinance, rural credit, and agri-finance. The low counts in Phase 1 therefore mark the timing of terminological adoption, not the intensity of research on rural finance. In phase 2 (2011–2015), the volume of research grew steadily with annual outputs rising from 1 (2011) to 6 (2014) and 11 papers in total (approximately 5.6%); this growth coincided with the emergence of financial inclusion on national and international policy agendas This is evident as, in 2015, financial inclusion also became a critical component of the Sustainable Development Goals (SDGs), referenced in seven of the 17 SDGs. This initiative was strongly endorsed by UN representatives from various nations and received particular backing from the Group of Friends of Financial Inclusion. During this period, the importance of financial access and usage became recognized by large international organizations such as the Bill & Melinda Gates Foundation, the World Bank Group with its Universal Financial Access 2020 initiative, and the IMF. In phase 3 (2016–2025), the outputs followed a steep, accelerating trajectory: 4 (2016), 7 (2017), 11 (2018), 12 (2019), 16 (2020). After a temporary dip to 9 (2021), productivity surged, eventually reaching a peak of 37 (2024) and 36 (2025). The data were retrieved in June 2026; therefore, the 2025 figures represent the full publication year. This phase accounts for well over 90% of the corpus, with 2018–2025 alone contributing nearly 88%, indicating a durable period of high productivity. This phase was driven by technological advancements. These include the proliferation of mobile money systems across Africa (building on post-M-Pesa agent networks and e-money regulation) and the rise of fintech platforms in Asia (e.g., digital-ID, e-KYC regimes, India's UPI, and large e-wallet ecosystems). These developments created rich settings for causal and measurement work. These infrastructures lowered transaction and onboarding costs, generated new administrative and platform data, and enabled quasi-experimental policy rollouts that are attractive to researchers.

Taken together, the inflection points around 2014 and 2016, along with the brief pandemic-era dip in 2021 followed by catch-up growth in 2022, and the persistently elevated outputs thereafter signal the consolidation of financial inclusion as a mainstream field, closely linked to the diffusion of digital financial services and fintech innovation and reinforced by policy agendas on poverty alleviation and the United Nations Sustainable Development Goals.

### *4.2. Countries with The Highest Number of Articles*

Table 2 presents the distribution of scientific production by country. Following standard bibliometric practice, we attribute each article to every country represented in the authors' affiliations. Consequently, internationally co-authored articles are counted once for each participating country, resulting in more country occurrences than the total number of articles. Figure 3 further illustrates the geographic distribution of publications across countries, with darker shades indicating a higher number of articles.

**Table 2.** Top countries by publications.

| Countries | Number | % (N/197) |
|---|---|---|
| China | 89 | 45.2% |
| India | 41 | 20.8% |
| Uganda | 15 | 7.6% |
| USA | 14 | 7.1% |
| South Africa | 13 | 6.6% |
| Malaysia | 12 | 6.1% |
| Nigeria | 10 | 5.1% |
| Australia | 5 | 2.5% |
| Ghana | 4 | 2.0% |

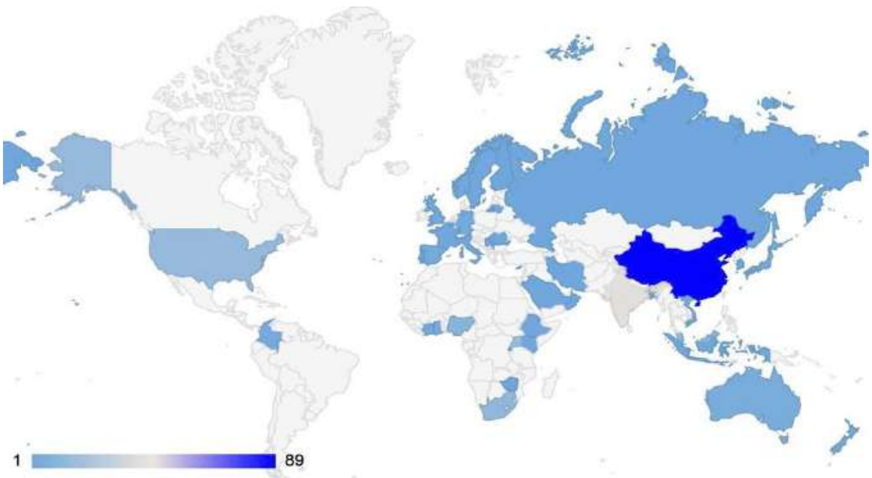


**Figure 3.** Geographic distribution of publications.

Overall, the majority of the publications originate from Asian and African countries. Among the countries contributing more than three publications, nine countries emerge as the leading contributors. China accounts for the largest share of publications (89, 45.2%), followed by India (41, 20.8%). Most of the remaining top contributors are developing economies: Uganda (15, 7.6%), South Africa (13, 6.6%), Malaysia (12, 6.1%), Nigeria (10, 5.1%), and Ghana (4, 2.0%). By comparison, only two developed countries—the United States (14, 7.1%) and Australia (5, 2.5%)—are represented among the leading contributors. Although China and India rank among the world's largest economies, sizeable income disparities within their populations continue to create substantial demand for financial inclusion across many rural areas and vulnerable social groups, which may explain the strong research interest in this topic. The strong presence of Sub-Saharan African countries (Uganda, South Africa, Nigeria and Ghana) suggests that financial inclusion is regarded as a particularly pertinent issue in developing regions, offering a useful lens for understanding how rural households and firms gain access to financial services.

### *4.3. Top Contributing Journals*

The publication landscape for this topic is skewed, with articles spread across a wide range of journals. However, as Table 3 shows, research is highly concentrated, with the top eight journals publishing nearly a third of all articles in the sample (61 out of 197, or 31%). The journal with the highest number of publications is Sustainability, with a total of 20 papers, accounting for 10.2% of the total output. As a broad-scope, interdisciplinary journal indexed under categories like "Environmental Studies," its leading role is significant. The journal's high output stems from a combination of factors, including its wide focus, an open-access model, and frequent special issues. These characteristics attract a substantial volume of submissions, which explains its position as the top publication outlet for this research topic. The next leading outlet is Finance Research Letters, with 13 publications, representing 6.6% of the total. This journal's focus on financial research underscores the topic's continued relevance within the traditional financial sector. The next tier includes China Agricultural Economic Review (6 articles) and Agricultural Finance Review (5 articles), which highlight the topic's strong relevance to applied fields such as agricultural economics. Finally, generalist journals like Applied Economics (4 articles) and International Journal of Social Economics (4 articles) confirm the topic's growing appeal outside of its original field.

**Table 3.** Top journals by publications.

| No | Title | Articles |
|---|---|---|
| 1 | Sustainability | 20 |
| 2 | Finance Research Letters | 13 |
| 3 | China Agricultural Economic Review | 6 |
| 4 | Agricultural Finance Review | 5 |
| 5 | Review of Development Economics | 5 |
| 6 | Applied Economics | 4 |
| 7 | Cogent Economics and Finance | 4 |
| 8 | International Journal of Social Economics | 4 |

### *4.4. Most Influential Authors*

Figure 4 illustrates the publication trajectory and citation impact of the ten most prolific authors over time. Each node's size represents the annual number of articles, while its color intensity indicates average citations per year. Two different models of scholarly contribution are apparent. One group, including Munene J.C., Ntayi J.M., and Malinga C.A., was most active during a concentrated period, primarily from 2016 to 2019. Their publication pattern suggests an episodic engagement with the topic, rather than a long-term research focus. In contrast, authors such as Li W., Wang J., and Zhang Y. have maintained consistent activity in more recent years. Li W.'s work is particularly noteworthy for its high publication volume and strong citation impact, as shown by the larger, darker nodes in Figure 4. This indicates a leading and highly visible role in the field.

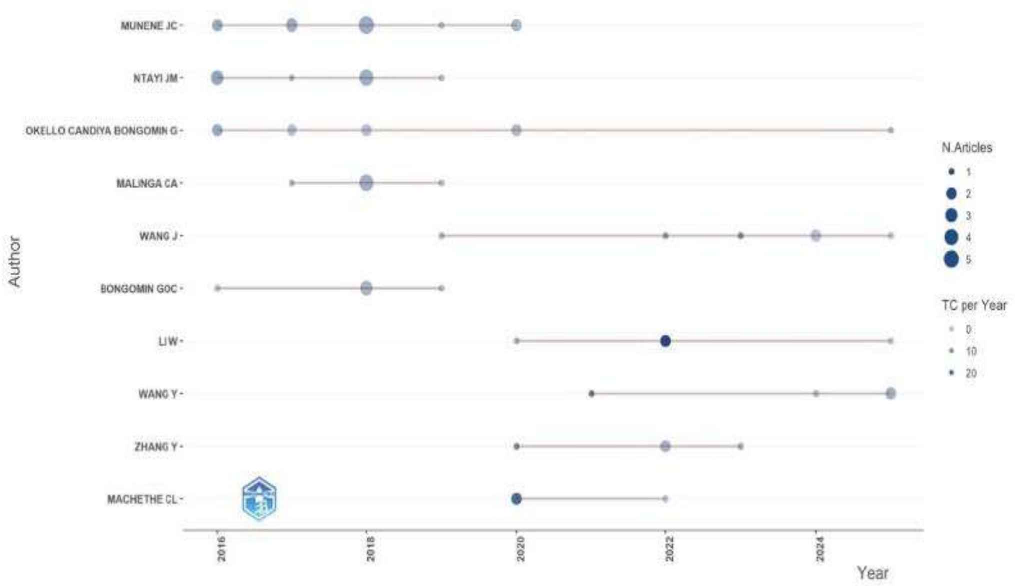


**Figure 4.** Annual publications and citation impact of top 10 authors.
**Note:** Bigger nodes mean more articles per year; darker color means more citations per year.

Meanwhile, Bongomin G. and Turvey C.G. exemplify sustained research over a long period. Although their yearly publication volume is modest, their enduring presence suggests a long-term commitment and a cumulative influence over time. Overall, this pattern highlights the varied nature of scholarly contributions, showing the field is shaped by both long-term, sustained research and short-term, intensive bursts of research.

### *4.5. Most Cited Articles*

Table 4 reports the most highly cited articles in our dataset. The article titled "Has digital financial inclusion narrowed the urban-rural income gap: The role of entrepreneurship in China" (Ji et al., 2021) ranks first with 151 Scopus citations (retrieved June 2026). Using data from 275 Chinese cities during 2014–2018, the study finds that digital financial inclusion significantly narrows the urban-rural income gap by promoting entrepreneurship. The effect is especially strong in regions with lower levels of economic development and education, highlighting digital finance as a timely support for reducing poverty and improving income distribution. Ranking second, "Bridging the financial inclusion gender gap in smallholder agriculture in Nigeria: An untapped potential for sustainable development" (Adegbite & Machethe, 2020) has accumulated 147 citations and the highest number of local citations within the 197-article corpus. The study reveals that the widening gender gap in financial inclusion, driven by socioeconomic, institutional, and cultural barriers, undermines agricultural productivity, income equality, and food security. To address this, priority should be given to digital finance and agricultural credit solutions designed specifically for women to advance gender equality (SDG 5). Other influential studies have significantly expanded the research agenda across several key areas. Wang and He (2020; 128 citations) find that DFI reduces farmers' vulnerability by improving their ability to cope with risk, while Wang and Fu (2022) identify specific mechanisms such as improved agricultural productivity and entrepreneurship. Concerning income disparities, Ji et al. (2021; 151 citations) note that DFI helps to narrow wage and property income gaps. Nevertheless, Huang and Zhang (2020) caution that inclusion might expand urban-rural inequality in the short run before narrowing it in the long term. C. Yu et al. (2022; 126 citations) focus on the rural consumption structure. The literature also addresses prerequisites and impacts (Niu et al., 2022), showing that broadband infrastructure improves DFI coverage, but actual usage depends on human capital. Aisaiti et al. (2019), when considering farmers' borrowing intentions and the moderating role of digital finance and social enterprises, indicated that promoting participation in social enterprises and digital finance, as well as implementing a systematic, comprehensive financial education project, is crucial for developing inclusive finance in rural areas. Liu et al. (2021), however, critically suggest that DFI might also reduce agricultural production by making non-agricultural activities more efficient.

**Table 4.** The most cited articles.

| Authors | Title | Year | Scopus citations |
|---|---|---|---|
| Ji X.; Wang K.; Xu H.; Li M. | Has digital financial inclusion narrowed the urban-rural income gap: The role of entrepreneurship in China | 2021 | 151 |
| Adegbite O.O.; Machethe C.L. | Bridging the financial inclusion gender gap in smallholder agriculture in Nigeria: An untapped potential for sustainable development | 2020 | 147 |
| Wang X.; He G. | Digital financial inclusion and farmers' vulnerability to poverty: Evidence from rural China | 2020 | 128 |
| Yu C.; Jia N.; Li W.; Wu R. | Digital inclusive finance and rural consumption structure – evidence from Peking University digital inclusive financial index and China household finance survey | 2022 | 126 |
| Yu N.; Wang Y. | Can digital inclusive finance narrow the Chinese urban–rural income gap? The perspective of the regional urban–rural income structure | 2021 | 104 |
| Liu Y.; Liu C.; Zhou M. | Does digital inclusive finance promote agricultural production for rural households in China? Research based on the Chinese family database (CFD) | 2021 | 103 |
| Niu G.; Jin X.; Wang Q.; Zhou Y. | Broadband infrastructure and digital financial inclusion in rural China | 2022 | 94 |
| Huang Y.; Zhang Y. | Financial Inclusion and Urban-Rural Income Inequality: Long-Run and Short-Run Relationships | 2020 | 88 |
| Wang X.; Fu Y. | Digital financial inclusion and vulnerability to poverty: evidence from Chinese rural households | 2022 | 86 |
| Aisaiti G.; Liu L.; Xie J.; Yang J. | An empirical analysis of rural farmers' financing intention of inclusive finance in China: The moderating role of digital finance and social enterprise embeddedness | 2019 | 82 |

Overall, the table reveals several dominant streams: income-gap dynamics (including short-run vs. long-run effects), gendered inclusion in smallholder agriculture, poverty vulnerability and reduction mechanisms, and the critical assessment of infrastructure and agricultural production decisions. It also shows a geographic concentration of evidence in China and Nigeria, which together anchor the contemporary discussion on rural digital financial inclusion.

### *4.6. Keyword Co-Occurrence Analysis*

Figure 5 shows the keyword co-occurrence map produced by VOSviewer (van Eck & Waltman, 2010). From 510 author keywords, 31 keywords that appeared at least four times were selected. In the network, each node represents a keyword, and its size reflects its frequency. Links between nodes indicate that the connected keywords co-appear in the same articles, while the thickness of the link represents the strength of these co-occurrences (Donthu et al., 2021). VOSviewer grouped the keywords into five clusters, each shown in a different color. Cluster 1 (Blue) centers on financial inclusion and its relationship with income inequality, with a particular focus on the roles of financial education and financial institutions, often in developing countries such as India. Cluster 2 (Green) focuses on digital financial inclusion and its impact on rural development, the urban-rural income gap, and entrepreneurship. Notably, it includes sophisticated analytical terms used to measure these impacts, such as "threshold effect," "Theil index," "heterogeneity," and "mediating effect." Cluster 3 (Yellow) focuses on financial access for vulnerable populations, specifically poor households in rural areas, looking at social capital, social networks, and institutional support. The Red cluster (Cluster 4) links fintech and mobile money, which drive the digital economy and rural inclusive finance to achieve sustainable development, climate resilience, and improve the agricultural sector. Cluster 5 (Purple), the smallest, connects traditional banking and savings with gender equality.

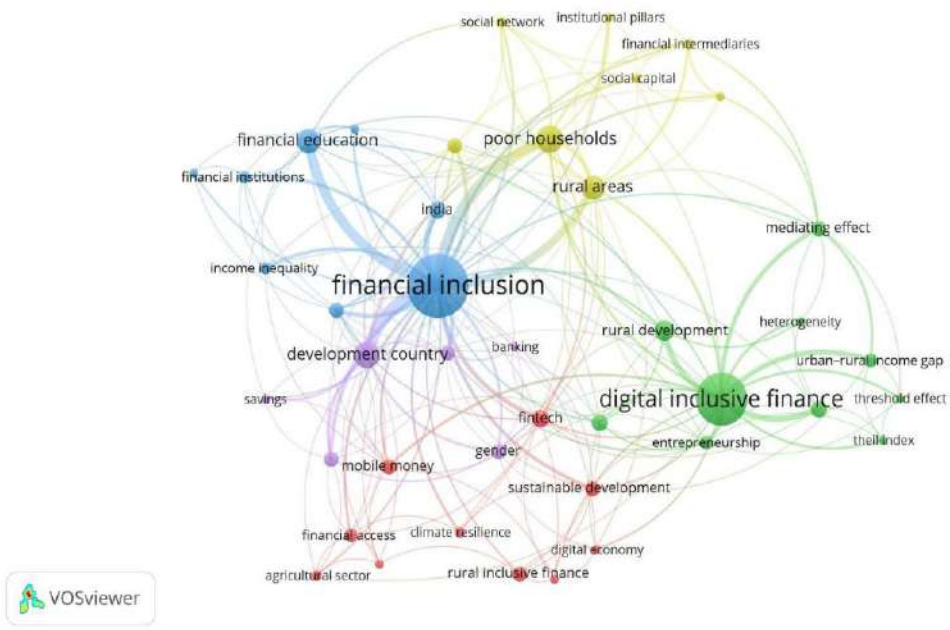


**Figure 5.** Keyword co-occurrence network.

Figure 6 presents the overlay visualization, a valuable tool for analyzing the temporal distribution of terms across clusters. In this visualization, colors range from purple to green to yellow, representing the chronological order in which keywords appear. In the overlay visualization, the research trends move from traditional financial inclusion for the poor to the impact of digital financial inclusion on rural development and entrepreneurship. Along the way, attention has also increased to the roles of technology, gender, and sustainable development trends.

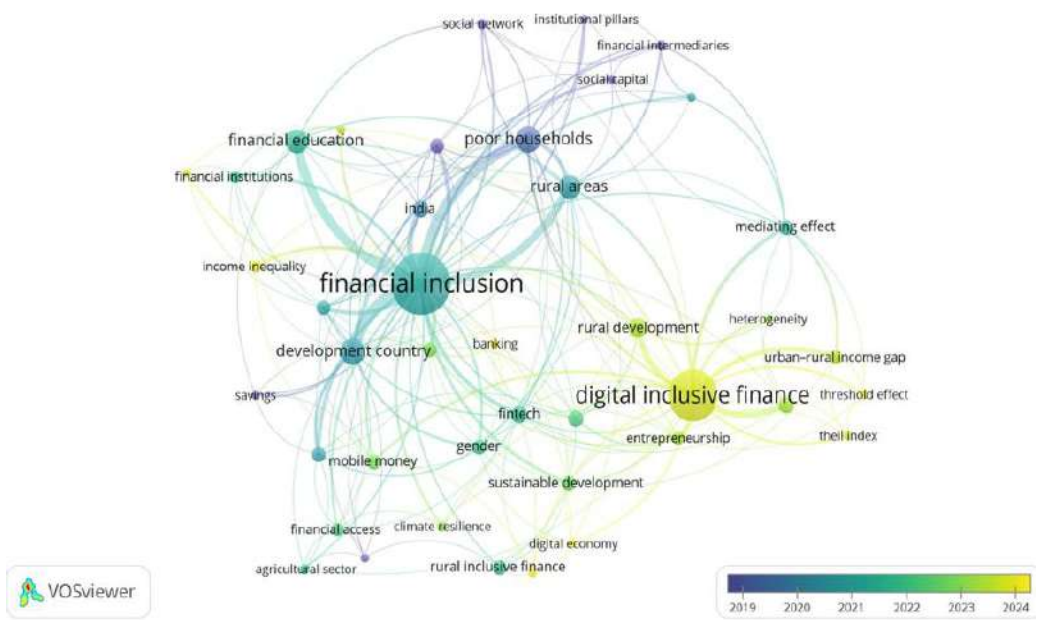


**Figure 6.** Overlay Visualization of Keyword Co-occurrence.

*4.7. Thematic Analysis and Findings*

4.7.1. Theme 1: Rural Financial Inclusion – Access, Impact and Sustainability

Consistent with its label, this cluster focuses on the core dimensions of rural and agricultural financial inclusion. At its core, financial inclusion concerns whether individuals, particularly those in rural areas, can access and effectively use formal financial services. Access to such services has been associated with higher incomes and improved quality of life. Accordingly, research in this cluster centers on three interrelated themes: (a) expanding access to financial services, often through fintech or digital channels; (b) assessing the socioeconomic impacts of financial inclusion; and (c) promoting the sustainability of financial inclusion in rural areas, where many people remain poor and underserved. The representative studies discussed below illustrate how the three dimensions shape this thematic cluster.

Financial inclusion delivers essential financial services through commercial banks and traditional financial institutions, extending access to remote areas and reducing barriers to financial participation (Sarma & Pais, 2011). With the development of technology, current studies on financial inclusion, including in agricultural and rural areas, are all directed towards the influence of technology, and the term "digital financial inclusion" is used and focused on in most studies (Fu et al., 2024; Wang & He, 2020; L. Zhang et al., 2023). Digital financial inclusion is considered a subset of financial inclusion that leverages technology platforms such as the internet, blockchain, AI, IoT, and cloud computing to broaden the scope of fintech services and non-traditional financial solutions, including mobile money, e-wallet, internet banking, P2P lending, and insurtech. P2P lending platforms enhance financial inclusion, especially in regions that lack traditional financial institutions, such as rural areas (Maskara et al., 2021). Digital financial inclusion greatly expands the coverage of financial services and accelerates digitization, enabling rural workers to access credit, promotes employment, raises incomes, and helps narrow the rural - urban wealth gap (Han et al., 2025; Mo et al., 2024). E-commerce policy has been shown to support improvements in digital financial inclusion in rural areas (Z. Zhang et al., 2024). However, the evidence in this cluster has notable limitations. Most studies measure access (e.g., account ownership) rather than the quality and continuity of financial service usage (Johnen et al., 2025; Panakaje et al., 2023). Moreover, many rely on short-term cross-sectional data, limiting their ability to assess whether welfare improvements among rural populations are sustained over time (Bongomin et al., 2023; Negera et al., 2025).

Research also demonstrates the multifaceted impact of rural financial inclusion. By expanding access to savings, credit, and investment services, financial inclusion promotes employment and increases incomes (Han et al., 2025; Mo et al., 2024). These benefits translate into micro-level outcomes such as poverty alleviation among farming households (Mhlanga, 2021) and broader macro-level effects, including a reduction in the urban–rural income gap (Ran et al., 2020). More recent studies further nuance this understanding by identifying digital technology as a key moderating factor that amplifies the positive influence of financial services on farmers' well-being (Li et al., 2025). Financial inclusion also has a significant positive impact on improved nutrition and helps reduce the gender gap between food expenditure and nutrition of female- and male-headed households (Bali Swain & Nsabimana, 2024). In the agricultural sector, the usage of financial services through financial inclusion has significant impacts on agriculture both in the short run and long run (Olaniyi, 2017).

Financial inclusion also links to climate resilience and sustainable development. Negera et al. (2025) found that financial inclusion strengthens the climate resilience of rural households, making it a key pillar of climate action and an essential driver of sustainable development. Improving financial inclusion is critical for sustainable agricultural development in rural areas, and facilitating both traditional and non-traditional financial service providers would help to stimulate agricultural growth (Olaniyi, 2017). Furthermore, according to Jena (2025), fintech adoption enhances financial inclusion by closing the inclusion gap, empowering rural populations, and helping to achieve various Sustainable Development Goals.

Overall, the literature agrees that expanding financial access and usage is critical, and that digital channels are the key to achieving this at scale (L. Zhang et al., 2023). However, significant questions remain about long-term provider viability and user equity. Key debates include the financial viability of providers in rural thin markets; the risk of digital exclusion from strict requirements like e-KYC, smartphone ownership, and biased scoring algorithms (Bongomin et al., 2023); and the fundamental question of which outcome should guide policy - whether it be provider viability, household welfare, or climate resilience. The effects of financial inclusion also depend heavily on local context, including infrastructure, data protection, and social factors like gender and trust (Ozili, 2025). These debates point to research gaps in common provider-viability indicators, rural agents' business models, and rules for privacy-by-design and fair algorithmic scoring.

#### 4.7.2. Theme 2: Digital Finance's Role in Rural China's Development

China, as the world's most populous country with a vast rural population, the third-largest land area, and strong agricultural development, has contributed the largest number of studies on financial inclusion. Over the past decade, China has become one of the pioneering countries in developing fintech services, with substantial capital and technological investment from both financial institutions and big tech firms. The rapid development of fintech has made digital finance a central research theme in rural China's financial inclusion. It has also enabled the creation of comprehensive digital financial databases, giving Chinese researchers access to rich datasets that are often unavailable or less accessible in many other countries, including the Peking University Digital Financial Inclusion Index (Han et al., 2025), the China Household Finance Survey, the Rural Financial Inclusion Survey, and firm-level data from fintech companies such as Ant Group. Research has consistently demonstrated that digital financial inclusion affects China's rural revitalization and the well-being of rural farmers (Le & Aralas, 2025; Li et al., 2025; Xia & Kong, 2024). Rural revitalization is measured by many factors, including industry, farming technology, healthcare, and quality of life. The impact varies across regions; western and central China show significantly stronger effects than other regions. Some studies have focused more on assessing the impact of financial inclusion in promoting and restructuring rural residents' consumption, boosting economic growth (Z. Zhang et al., 2024), driving rural industrial prosperity (L. Zhang et al., 2023), fostering entrepreneurial activities of farmers (Le & Aralas, 2025) and reducing the income disparity between urban and rural regions (Aik & Zhang, 2023; Ran et al., 2020). Gender issues have received much attention in several Chinese studies; for example, Shao et al. (2023) examine the role of financial inclusion in promoting entrepreneurship. In the agricultural sector, research has proved that agricultural resource allocation and agricultural production are impacted by digital financial inclusion (X. He et al., 2025; Liu et al., 2021).

Although substantial Chinese research supports the significant contribution of digital finance to rural revitalization, entrepreneurship, and narrowing the urban–rural income gap, the findings remain subject to ongoing debate. First is the question of external validity: whether these findings can apply to other countries, given China's unique market and regulatory environment. Second, many studies need stronger causal identification, prompting calls for more quasi-experimental research. Third, the dominant role of Big Tech firms raises important questions about market competition, the risk of crowding out local banks, and data privacy. These debates point to research gaps around the transferability of the Chinese model to other developing economies and the use of staged technology rollouts as natural experiments for causal identification.

#### 4.7.3. Theme 3: Rural Financial Inclusion: Literacy, Digitalization, and Empowerment

Research in this area examines the multidimensional nature of financial inclusion, encompassing financial literacy, digital transformation, and socioeconomic empowerment. Particular attention has focused on digital financial inclusion rather than traditional financial services, reflecting the rapid advancement of digital technologies and fintech in recent years. In rural areas, where dispersed populations and geographical barriers often limit access to conventional banking, digital financial services play a crucial role in expanding financial inclusion.

However, another important characteristic of rural areas that can hinder access to financial inclusion is limited education and financial knowledge compared to urban areas. To promote financial inclusion, these root causes must be addressed, and many studies worldwide have identified and focused on these issues. According to Antil et al. (2022), among the key predictors of financial inclusion among rural agricultural households, education level is the most significant factor. By raising awareness of financial services' availability and benefits, especially in low- and middle-income countries such as India, China, Nigeria, Uganda, and Ghana, financial literacy helps ensure financial inclusion in rural areas (Atkinson & Messy, 2013). In this relationship, network actors, financial institutions, digital access, and social capital have played mediating roles (Bongomin et al., 2016a; Bongomin et al., 2016b; Bongomin et al., 2020). Studies in this area also pointed out that, through financial inclusion, socio-economic empowerment is improved, and sustainable goals (SDGs) can be achieved (Dash & Mohanta, 2024; Panakaje et al., 2023).

A synthesis of the literature suggests that rural financial inclusion extends beyond expanding access to basic banking services. Rather, it is shaped by the interaction of three broad factors: individual capabilities, digital infrastructure, and the institutional environment. Financial literacy provides an essential foundation, but its benefits depend on whether it translates into sound financial behaviors and decisions. Likewise, digital technologies can accelerate financial inclusion, yet their effectiveness depends on reliable infrastructure, adequate digital skills, and equitable access. The institutional environment also plays a critical role, as trust, social norms, consumer protection, and supportive regulations influence whether rural populations are willing and able to engage with formal financial services. Within this context, trusted intermediaries, such as cooperatives and local financial advisors, can help bridge the gap between financial institutions and rural users. Taken together, these findings point to several areas requiring further attention. The literature highlights the need for more effective channels to deliver financial education through trusted local institutions, stronger digital infrastructure and capacity-building to ensure that digitalization reduces rather than reinforces exclusion, and more robust consumer protection frameworks to foster trust and safeguard vulnerable rural users.

#### 4.7.4. Theme 4: Rural Financial Inclusion and Poverty Alleviation

Poverty and the income gap between urban and rural populations are major challenges for many developing and less-developed countries (Agwu, 2021). Therefore, studies on financial inclusion in rural areas worldwide examine whether greater access to financial services can increase income and reduce poverty, particularly given the significant regional and demographic disparities in rural communities. Digital financial inclusion is confirmed to provide a significant inhibitory impact on rural poverty (Luo & Chen, 2025; Pei et al., 2024) and narrow the rural-urban income gap and consumption structure (Yang et al., 2025; N. Yu & Wang, 2021). Relating to the impact mechanisms, studies in this area have indicated that access to finance helps the poor access community savings clubs and microfinance institutions (Abraham, 2018), increases their income, and affects both crop and livestock diversification, which leads to an impact on their access to food, dietary diversity, and nutritional structure (Murendo et al., 2021). Research on financial inclusion in agricultural and rural areas has not only stopped at using empirical analysis to identify problems and impacts, but a few recommendations have been suggested to encourage the development of financial inclusion in this area, which is considered to be more disadvantaged and challenging. Several studies, such as Bongomin and Munene (2020) and Hu et al. (2024), identify effective ways to promote financial inclusion and strengthen resilience against poverty. These include improving financial literacy, easing credit constraints, and applying appropriate account-opening fees. They also recommend designing financial products that are convenient, flexible, reliable, continuous, safe, and secure, while strengthening households' risk-coping capacity.

Synthesizing these findings, while the consensus is that digital financial inclusion (DFI) helps reduce rural poverty and narrow income gaps by easing credit constraints and enabling better investment, the literature highlights crucial nuances. The impact is often heterogeneous; for instance, in China, benefits vary regionally, showing stronger effects in less-developed areas and non-linear patterns across different types of spending. Similarly, in Uganda, digital literacy levels strongly moderate the impact of financial technologies on vulnerable groups (Bongomin et al., 2023). At the same time, the evidence suggests that DFI is far from a complete solution. Its effectiveness is limited in areas with weak local industries, particularly affecting self-employment income. Furthermore, barriers to usage remain significant. As seen in Uganda, poor product fit, such as high upfront fees and minimum balances, along with weak client protection, significantly reduces uptake. Studies also caution that without proper safeguards, risks like over-indebtedness can offset the benefits. Taken together, the evidence in this cluster points to DFI as a partial rather than complete solution: its welfare and poverty-reduction effects appear conditional on complementary factors, including rural digital infrastructure, user skills, consumer protection, and real-sector development.

#### 4.7.5. Theme 5: Financial Inclusion – Global Rural Perspectives

Research on financial inclusion in agricultural and rural areas has been extensively explored globally, with the most focus on studies in China, India, and a range of African countries such as Nigeria, Zimbabwe, Rwanda, Uganda, Ghana, and Kenya. In countries other than China, high poverty rates, wide rural-urban income gaps, and very limited access to financial services in rural areas have drawn strong research interest, with scholars seeking solutions to enhance financial inclusion. In India, Jena (2025) examines factors influencing fintech adoption to enhance financial inclusion. Besides, other studies have provided evidence on determinants of financial inclusion for the poor in developing economies, especially in rural Uganda, which include both direct and mediating factors (Bongomin et al., 2016a; Bongomin et al., 2016b; Bongomin et al., 2020). In Rwanda, Bali Swain and Nsabimana (2024) show that financial inclusion improves nutrition in rural areas. In Zimbabwe, Mhlanga (2021) demonstrates that financial access helps reduce poverty in agriculture. For middle-income countries, including Nigeria, technology has been proven to narrow the gap between rural development and financial inclusion (Agwu, 2021). A more comprehensive study by Baborska et al. (2020) across 88 low- and middle-income countries showed the impact of financial inclusion on food access and food security. In general, the research mainly focuses on some common key issues but addresses specific situations of each country or region, such as the factors and challenges affecting financial inclusion, the role of digital financial services for rural residents, the impacts on agricultural production, and recommendations to narrow income and livelihood gaps, promote equitable development, and reduce poverty. A rare European study, focused on rural Romania, presents a model based on non-bank financial institutions (Yue et al., 2019). In this model, such institutions invest in financial technology and offer flexible services suited to individual needs, especially in remote rural areas. The authors suggest that this model could be applied in other countries to expand financial inclusion. Gender is also a global concern in rural financial inclusion. Women often face more barriers in accessing finance, such as patriarchal bias, discrimination, and social norms, especially in poor countries (Manta, 2019). The severity and form of these barriers, however, differ markedly across regions. Studies from Sub-Saharan African contexts tend to emphasize documentation requirements and mobility constraints, whereas research in South Asian settings gives greater weight to household decision-making structures and social sanctions (Dash

& Mohanta, 2024). This variation indicates that gender-responsive approaches face substantial transferability challenges across contexts.

Overall, while technology like FinTech and mobile banking is seen as a powerful tool, its success is not automatic. A major challenge is overcoming deep psychological and cultural barriers; therefore, simply providing the infrastructure is not enough. A further tension runs through this literature: digital channels offer efficiency, yet many rural users continue to value the personal relationships and trust embedded in informal financial arrangements. Since rural residents often prefer familiar systems, an important question for future work is how the trust associated with traditional methods might be combined with the efficiency of digital services. The literature in this cluster identifies a shift in focus from basic access (having an account) toward deeper use (whether financial tools improve life and resilience), while noting that measuring this deeper impact remains methodologically difficult. Studies also converge on the observation that outcomes are highly context-dependent and are shaped by broader institutional conditions, including restrictive social norms (such as gender bias), regulatory gaps, and weak consumer protection.

Read together, the five themes reveal both convergences and tensions. Themes 1 and 4 both examine the welfare outcomes of financial inclusion, including income, poverty, and food security, but differ in their scope. Theme 1 adopts a broad development perspective, encompassing access to financial services, socioeconomic impacts, climate resilience, and sustainable development. In contrast, Theme 4 focuses more specifically on the pathways through which financial inclusion contributes to poverty reduction and related welfare outcomes. Themes 2 and 5 are geographically complementary. Theme 2 concentrates on the data-rich Chinese context, while Theme 5 assembles more fragmented evidence from India, several African countries, and Europe. They also differ methodologically: Chinese studies typically draw on large, nationally systematic datasets that combine administrative indices with established household surveys, while studies elsewhere rely more on smaller, region-specific surveys. Rather than focusing on specific outcomes, Theme 3 emphasizes the enabling factors - particularly financial literacy, digital capabilities, and institutional trust - that underpin effective financial inclusion and its broader socioeconomic benefits. Across the five clusters, this pattern aligns with a contingency view of rural financial inclusion in the literature: intervention effectiveness varies with the local mix of infrastructure, human capital, and institutional quality, rather than following a single universal mode.

Beyond the thematic findings, the empirical literature has also evolved methodologically. Early studies relied mainly on cross-sectional regressions, whereas more recent research increasingly uses panel data models, instrumental variable approaches, difference-in-differences designs, and spatial econometric techniques to strengthen causal inference. While these methods improve the credibility of empirical findings, their effectiveness depends on the validity of their underlying assumptions. As a result, the strength of causal claims varies across studies, highlighting the need for more rigorous identification strategies in future research.

## 5. Discussions and Conclusions

Synthesizing 197 Scopus-indexed articles from 2000 to 2025, this study presents a bibliometric review of financial inclusion in agriculture and rural areas. Our analysis documents a significant shift from access-centric debates toward use- and impact-oriented analyses focused on digital financial services, entrepreneurship, gender equality, and sustainable development. The bibliometric evidence reveals a coherent intellectual structure composed of five interconnected research themes: (i) access, impact, and sustainability; (ii) digital finance in rural China's development; (iii) literacy, digitalization, and empowerment; (iv) poverty alleviation; and (v) global rural perspectives with persistent gender and regional heterogeneity. Sensitivity analyses that vary the keyword occurrence threshold confirm the stability of this five-cluster structure, supporting the robustness of our findings. Theoretically, this study advances the literature by providing an in-depth understanding of the multifaceted nature of financial inclusion in agriculture and rural communities, while practically, it identifies key priorities for policymakers, practitioners, and researchers, as outlined below.

This focus on rural and agricultural contexts distinguishes our review from previous bibliometric studies on financial inclusion. Ahiase et al. (2024) and Gallego-Losada et al. (2023) map the digital financial inclusion literature across all sectors, while Ghosh (2024) traces general financial inclusion trends and organizes the field around initiation, service delivery, and customer-centric design. While these reviews offer valuable insights, their broad sectoral scope leaves many rural- and agricultural-specific issues underexplored. By focusing on rural and agricultural studies, our review highlights sub-themes less visible in broader bibliometric mappings: the seasonality of farm cash flows, bundled savings-credit-insurance products, the fragility of cash-in/cash-out infrastructure in thin markets, and climate resilience as a distinct dimension of inclusion. These are not simply rural variants of urban problems; they reflect a different underlying logic of financial need.

Our analysis yields three cross-cutting insights to serve as a basis for policy recommendations. First, assessment must move beyond simple access metrics (such as account ownership rates) to focus on quality-of-use indicators: active use, transaction intensity, product stacking, affordability, service reliability and protection, disaggregated by gender and age. This shift also requires research that traces how DFI alters farm productivity and household resource allocation across smallholders with different land sizes, market access, and gender, so that products can be designed for particular farmer groups rather than for an average user. Second, product design should be livelihood-sensitive- supporting seasonal cash flow smoothing, bundled savings-credit-insurance, and climate risk cover - to close usage gaps. Progress here depends on clarifying which channels matter most: whether improved savings, insurance uptake, access to credit, or efficient remittances most strongly reduce vulnerability to shocks such as climate events, health crises, and market volatility. It also depends on understanding how financial and digital literacy interact with behavioral traits such as trust, risk preference, and time preference, since these jointly shape whether services are adopted and well used. Third, digital financial infrastructure is necessary but not sufficient. Meaningful welfare gains depend on the combination of three core elements: shared digital public infrastructure (such as identification systems and real-time payments), a wide and adequately funded network of transaction agents, and consumer protection rules suited to small, frequent transactions, limiting hidden fees or minimum balance requirements. Whether these elements deliver depends on local conditions, suggesting that future work should test how connectivity, digital ID, e-KYC systems, and governance quality moderate the effect of DFI on non-farm employment and rural structural transformation. For policymakers, these insights imply a pivot from expanding access to deepening and stabilizing use. And for practitioners, they underscore the need to align products and delivery channels with rural cash flow cycles, agent liquidity constraints, and last-mile frictions.

Gender emerges as a cross-cutting dimension across the themes. Rather than representing a distinct research theme, gender cuts across the literature as a factor that shapes both access to financial services and the benefits derived from their use (theme 1). The reviewed studies consistently show that women face greater barriers to financial inclusion, although the nature and consequences of these barriers vary across contexts. In the literature on access to financial services, women encounter greater obstacles to adopting and sustaining the use of digital financial services because of documentation constraints, limited mobility, and lower mobile phone ownership (theme 1). In theme 2 relating to financial inclusion in China, research on financial capability highlights how gendered household bargaining power influences rural women's entrepreneurial outcomes (Shao et al., 2023). Studies on poverty reduction (theme 4) show that narrowing gender gaps in smallholder agriculture is not only a matter of equity but also a key pathway to improving productivity and reducing poverty (Adegbite & Machethe, 2020; Bali Swain & Nsabimana, 2024). In theme 5, comparative studies demonstrate that gender-related barriers are highly context-specific, ranging from documentation and mobility constraints in Sub-Saharan Africa to household decision-making structures in South Asia (Dash & Mohanta, 2024; Manta, 2019). Collectively, these findings suggest that gender should be treated as a cross-cutting analytical lens, incorporating women's needs into the design of rural financial products, delivery channels, and consumer protection frameworks from the outset rather than addressing it as a secondary consideration.

Building on these insights, this review translates the key findings into four policy priorities that provide actionable guidance for key stakeholders. First, policymakers and financial service providers should shift their focus from expanding access alone to improving the quality and effective use of financial services by developing products and services that support sustainable livelihood improvements. Second, financial institutions should design context-specific financial products that reflect the diverse needs of rural and agricultural populations, taking into account seasonal income patterns, production cycles, and varying levels of financial capability. Third, governments, regulators, and infrastructure providers should strengthen the enabling environment by expanding digital connectivity, improving digital identity systems, enhancing regulatory transparency and consumer protection, and investing in digital literacy. Particular attention should also be given to improving smartphone access and digital capabilities among rural populations to facilitate the effective adoption of digital financial services. Finally, policymakers, financial institutions, and development organizations should adopt gender-responsive financial inclusion strategies that address the structural barriers limiting women's access to and effective use of financial services, while promoting their broader economic participation.

The literature's geographic concentration should also be acknowledged. As shown in Table 2, China accounts for 45.2% of the corpus, and this concentration is not neutral: it shapes the mechanisms, variables, and even the causal identification strategies that dominate the field. The Chinese literature reflects a highly specific institutional context - a nationwide big-tech-based platform ecosystem led by firms such as Ant Group and Tencent, a proactive state-led regulatory framework that permits rapid rollout, and a dense administrative data infrastructure (notably the Peking University Digital Financial Inclusion Index) that supports large-sample empirical work. These conditions are rare outside China. Consequently, the mechanisms most frequently identified in the Chinese literature—for example, DFI operating through digital entrepreneurship and platform-mediated credit access to narrow the urban-rural income gap—may not travel well to agricultural economies with different institutional configurations. In Sub-Saharan African contexts, for instance, the dominant channels tend to run through mobile-money agent networks, informal savings groups, and NGO-supported microfinance rather than through big-tech platforms. Similarly, in South Asian settings other than India, digital public infrastructure and household decision-making structures play a stronger conditioning role. The intellectual structure identified in this review largely reflects evidence generated in the Chinese context. Because institutional arrangements, governance quality, digital infrastructure, and socioeconomic conditions vary considerably across countries, the generalizability of specific findings and mechanisms remains uncertain. At the same time, these findings provide a useful foundation for future comparative studies across different agricultural and rural contexts.

In addition, based on the gaps identified in this review, we propose the following future research directions to strengthen the field's external validity and policy relevance. First, future research should move beyond examining whether financial inclusion improves income to better understand how it enhances agricultural livelihoods. This includes investigating its effects on farm productivity and household resource allocation across smallholders with different land sizes and levels of market access, while identifying the mechanisms through which financial inclusion reduces poverty and strengthens resilience. In particular, future studies should determine whether improved savings, greater insurance uptake, expanded access to credit, or more efficient remittance services are the primary channels through which financial inclusion mitigates vulnerability to climate shocks, health crises, and market volatility. Research should also examine how financial and digital literacy, together with behavioral factors such as trust, risk preferences, and time preferences, influence the adoption and effective use of financial services. Second, future research should focus on making financial inclusion more responsive to the diverse needs of rural populations. Studies should explore how financial services can be tailored to farmers with different socioeconomic characteristics, production conditions, and cash-flow patterns in order to reduce transaction costs, improve access to appropriate financial products, and encourage sustained use. Particular attention should be given to addressing persistent gender disparities by evaluating the effectiveness of targeted digital-literacy and empowerment programs, thereby providing evidence for more gender-responsive financial inclusion policies. Finally, future research should pay greater attention to the contextual conditions under which financial inclusion generates development outcomes and to the generalizability of existing evidence. Studies should investigate how digital infrastructure, including connectivity, digital identity, and e-KYC systems, together with local governance quality, shape the effectiveness of financial inclusion in promoting non-farm employment and rural structural transformation. Because much of the current evidence comes from rural China, future work should also assess whether existing models, measurement approaches, and empirical findings transfer to other agricultural economies, particularly in Africa and other developing regions. Although the broader financial inclusion literature has extensively studied the relationship between financial access and household vulnerability and the effectiveness of gender-focused programs, important knowledge gaps remain in rural and agricultural settings. Seasonal livelihoods, climate-related risks, and differences in the quality of financial service use create context-specific measurement and implementation challenges that evidence from more general populations cannot fully explain. Moreover, methodologically, future research should also strengthen causal inference by adopting more rigorous identification strategies and conducting comprehensive robustness and validation tests where appropriate.

This study has several limitations. First, our analysis rests exclusively on articles indexed in Scopus, which, despite its extensive coverage, introduces an English-language bias and potentially underrepresents research from the Global South published in regional journals or local languages. A substantial body of influential work in this domain also exists as grey literature, policy reports from the World Bank, CGAP, central banks, and major non-governmental organizations - which our approach excludes. Future bibliometric reviews could systematically integrate both academic and grey literature to provide a more comprehensive and practice-informed understanding of the field. Second, we restricted the search to articles using "financial inclusion" in their titles to preserve the conceptual consistency of the bibliometric analysis. As a result, related literature, including "microfinance," "rural credit," and "agricultural finance," was excluded despite their role as intellectual antecedents. Future bibliometric studies could adopt broader search terms to trace the intellectual evolution from microfinance to financial inclusion. Third, text harmonization and keyword standardization inevitably involve some researcher judgment that may influence clustering outcomes. To enhance robustness, we tested alternative minimum keyword occurrence thresholds, all of which consistently produced the same five-cluster structure. While this supports the internal stability of the intellectual maps, it does not eliminate the inherent subjectivity associated with bibliometric preprocessing.

Overall, the knowledge structure mapped in this bibliometric review indicates a gradual shift from studies of financial access to research exploring the use and developmental outcomes of financial inclusion in agriculture and rural contexts. The evidence synthesized in this review suggests that future progress will depend not only on expanding access but also on improving the quality, appropriateness, and effective use of financial services. Achieving durable gains in welfare, agricultural productivity, and household resilience will require rigorous impact evaluation, context-specific product design, and continued investment in the digital and institutional infrastructure that enables affordable, secure, and reliable financial transactions.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AI | Artificial Intelligence |
| CGAP | Consultative Group to Assist the Poor |
| DFI | Digital Financial Inclusion |
| e-KYC | Electronic Know Your Customer |
| IMF | International Monetary Fund |
| IoT | Internet of Things |
| P2P | Peer-to-Peer (lending) |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| SDG | Sustainable Development Goal |
| UPI | Unified Payments Interface |

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# Influence of Community-Based Agriculture and Rural Development Projects on Poverty Reduction in Nigeria: The Moderating Role of Community Participation

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**Abstract:** Rural Nigeria faces persistent poverty, where agriculture remains the primary livelihood for the largely rural population. However, although Community-Based Agriculture and Rural Development Projects (CBARDP) have been widely implemented, the extent to which community participation strengthens their poverty-reduction outcomes remains insufficiently examined, particularly using a comprehensive Structural Equation Modelling (SEM) approach. This paper discusses how Community-Based Agriculture and Rural Development Projects (CBARDP) reduce poverty in Nigeria with the community participation as a moderator. Primary data were collected from 385 rural household heads using a quantitative cross-sectional survey design. Respondents were selected through multistage stratified random sampling across the North-West, North-East, and South-South geopolitical zones of Nigeria, yielding a 96.25% response rate. The findings revealed that Community-Based Agriculture Projects (CBAP) exerted a significant positive direct effect on poverty reduction ($\beta = .189$, $p < .001$), whereas Rural Development Projects (RDP) did not. Community participation both directly reduced poverty ($\beta = .237$) and significantly strengthened the effects of CBAP ($\beta = .304$) and RDP ($\beta = .215$) on poverty reduction. The moderation model elucidated 47% of the variance in poverty alleviation. These results show that meaningful community involvement is not just an extra step, but a necessary step to turn investments in agriculture and rural development into long-term poverty reduction in Nigeria. While the cross-sectional design limits causal inference, the model explains substantial variation in poverty reduction and provides a robust basis for future longitudinal investigations.

**Keywords:** Community-Based Agriculture; community participation; poverty reduction; rural development



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## 1. Introduction

Poverty remains a significant socio-economic issue facing developing countries, especially sub-Saharan Africa, where a large proportion of the population relies on agriculture to earn a living (Dimnwobi et al., 2023). Nevertheless, decades of development interventions and economic reforms have left most rural communities with restricted access to economic opportunities, infrastructure, and social services. In Nigeria, poverty is mostly an urban phenomenon, experienced primarily in rural regions where farming is the main source of local economic activity. Rural families have tended to use subsistence farming, which is low-productivity, characterized by limited access to modern farming technologies, poor infrastructure, and limited institutional support (Vasavi et al., 2025). Such structural issues have led to low development and high poverty levels in most rural areas of the country.

Nigeria is endowed with extensive agricultural resources, including fertile land, favorable climatic conditions, and a large labor force, which can sustain agricultural production. Nonetheless, the agricultural sector has not been able to play its full role in economic development and poverty alleviation. Several limitations, including limited access to credit facilities, poor extension services, low market connectivity, and inadequate rural infrastructure, have constrained productivity in the sector. Consequently, a large number of smallholder farmers are caught in low-productivity and poverty cycles. Given the close association between rural living and agriculture, enhancing agricultural production and intensifying rural development programs have been placed on Nigeria's policy agenda.

Rural development is a multidimensional concept that enhances the economic, social, and institutional status of rural people. It involves several interventions to increase agricultural productivity, provide the necessary infrastructure, and give rural communities a chance to participate in development processes and access markets and services. Governments and development agencies have, over the years, undertaken numerous rural development programmes to address poverty and ensure sustainable development in rural regions (Forkuor & Korah, 2023). Nevertheless, the outcomes of many of these programmes have been mixed due to issues with project implementation, institutional weaknesses, and a lack of community participation.

To address these issues, development practitioners have repeatedly stressed the importance of participatory and community-based approaches. The Community-Based Agriculture and Rural Development Projects (CBARDP) is one such measure that aims to empower rural communities by directly engaging them in development activities. These initiatives aim to enhance agricultural output, develop rural infrastructure, and improve livelihoods through locally led initiatives responsive to rural communities' demands and concerns. CBARDP is based on grassroots involvement, collective decision-making, and ownership of development programs in contrast to the classic top-down developmental policies.

Community-based development methods have become widely recognized in the global development discourse. Development agencies and scholars argue that community participation in the formulation and implementation of development projects can significantly enhance their effectiveness and sustainability. Participatory development approaches, according to Dushkova and Ivlieva (2024), allow communities to recognize and define their own needs and priorities, thus making development interventions more pertinent and responsive to local conditions. On the same note, Mehedi Hasan et al. (2026) suggest that service delivery, stronger local institutions, and improved accountability could be enhanced if communities are actively involved in development processes through community-driven development programmes.

Nigeria has witnessed the implementation of several community-based agricultural and rural development projects aimed at alleviating rural livelihoods and minimizing poverty. Two of the most notable ones include the Fadama Development Projects, the Community and Social Development Project (CSDP), and other rural development programmes assisted by the donors (Nura, 2022). The efforts have aimed to increase agricultural productivity, expand access to productive resources, and empower community institutions through participatory development mechanisms. For example, the Fadama mobilized farmers into user groups, helped them establish their development priorities, and shared the project's resources. According to programme evaluation evidence, these initiatives have led to increases in agricultural productivity, household income, and community access to infrastructure (Ashoro et al., 2024).

Although many rural development programmes have been instituted in Nigeria, poverty remains widespread in most rural areas. Jaiyeola and Bayat (2020) indicate that a significant proportion of the rural population in Nigeria remains below the poverty line. Such long-standing poverty raises critical questions about whether development interventions are effective and, under what circumstances, they can have significant socio-economic implications. Although community-based agricultural development initiatives are meant to enhance rural livelihoods, the success of such endeavors is normally pegged to several contextual and social factors.

Community participation is one of the key elements that determines how effective development projects are. Community participation is the active involvement of the community in the planning, implementation, monitoring, and evaluation of community development activities that impact their lives. Participation allows community members to share their knowledge, air their demands, and provide input on decisions regarding how to distribute and exploit development resources. Communities that engage in development projects through active participation develop a sense of ownership and responsibility, thereby increasing the sustainability and effectiveness of the projects (Uzorka et al., 2024).

Nevertheless, in addition to its direct effects on the development outcome, community participation may also shape the relationship between development interventions and poverty reduction. That is, involvement may affect the success of community-based development projects in bringing about significant socio-economic change in rural communities. Statistically, this implies that community participation can be a moderating variable on Community-Based Agriculture and Rural Development Projects and poverty reduction.

Community involvement would enhance the success of agricultural development initiatives in several ways. First, the involvement will help incorporate local knowledge and indigenous practices into development planning, thereby enhancing the relevance and flexibility of the development interventions. Second, participatory processes enhance transparency and accountability in project management, as community members can monitor project activities and ensure that resources are used properly. Third, participation enhances social capital within communities by promoting cooperation, trust, and collective action among community members (Portes, 1998).

Community participation in agricultural development projects is usually through systems such as farmer cooperatives, participatory planning workshops, community monitoring committees, and local development associations. Through these participatory structures, farmers and other community members can work together to address common development issues. This kind of cooperation can increase resource mobilization, knowledge sharing, and the adoption of better farming techniques.

Despite the importance of community participation in development initiatives, little research has examined its moderating effect on the effectiveness of agricultural and rural development programmes in Nigeria. This paper examines the influence of Community-Based Agriculture and Rural Development Projects (CBARDP) on poverty reduction in Nigeria. The study aims to contribute to the broader research on participatory development and poverty reduction in rural areas by exploring the effects of participation in community-based development programs on program effectiveness.

## 2. Literature Review

### *2.1. Poverty and Rural Development in Nigeria*

Poverty is one of the most pressing development problems facing most developing nations, especially in sub-Saharan Africa, where large numbers of citizens are rural. Nigeria is a country with abundant natural and human resources, yet it remains poor, with the majority of the poor living in rural communities (Prince et al., 2023). Low-income rates, inaccessibility to basic social amenities, ineffective infrastructure, and unavailable economic opportunities usually define poverty in rural areas. Akoji and Abaji (2025) report that more than 60 percent of Nigerians are multidimensionally poor, with the largest percentage of that group living in rural areas. Such statistics highlight the socio-economic imbalances involved between the rural and urban regions of the country.

Agriculture has been an important part of the rural economy in Nigeria and has remained the main means of livelihood for a large number of the population. The industry plays a significant role in creating employment, ensuring food security, and driving economic growth. Nevertheless, the type of agriculture used by most rural societies is largely subsistence farming, characterized by low productivity, limited access to new technology, limited credit facilities, and limited extension services. These limits have, to a great extent, reduced rural households' ability to raise their incomes and escape poverty.

As a result, rural development has been a major concern for national and international development policies, aimed at addressing the structural causes of poverty in rural communities. Rural development is a broad term that encompasses a range of strategies aimed at improving the economic, social, and institutional conditions of rural populations. The main measures in these strategies are usually aimed at enhancing agricultural output, rural infrastructure, market accessibility, and community empowerment (Abubakar, 2022). The recent decades have been characterized by the growing significance of participatory and community-based approaches among development scholars and practitioners in their rural development programs

### *2.2. Community-Based Agriculture and Rural Development Projects (CBARDP)*

Community-Based Agriculture and Rural Development Projects (CBARDP) are a form of participatory development that focuses on the role of local communities in planning, executing, and managing development projects. The projects are meant to boost agricultural productivity and rural livelihoods, and to alleviate poverty by delivering locally initiated solutions. In contrast to traditional top-down approaches to development, in which an outside authority makes decisions, CBARDP emphasizes local knowledge and community needs, as well as grassroots involvement.

CBARDP typically encompasses numerous measures to empower rural economies. These interventions can include providing better agricultural inputs, irrigation facilities, farmer training programmes, developing rural roads, market access initiatives, and cooperative development. With a blend of agricultural assistance and community development programs, CBARDP aims to support sustainable development that enhances the overall quality of life of people in rural areas.

International development organizations such as the World Bank, the Food and Agriculture Organization (FAO), and the International Fund for Agricultural Development (IFAD) have strongly encouraged a community-driven approach to development. Awoyemi and Oke (2024) suggest that community-based development initiatives may enhance service delivery and accountability, and strengthen local governance structures when communities participate in project implementation. Community involvement makes development interventions more relevant and enhances sustainability by fostering a sense of ownership.

In Nigeria, several community-integrated agricultural development programmes have been implemented to enhance rural livelihoods. Some of the most recognizable projects are the Fadama

Development Projects, which the World Bank sponsored to raise agricultural productivity and rural incomes through community-level development mechanisms. These projects enabled local farmers to form user groups, determine development priorities, and even manage project resources together. Assessments of such programmes have revealed that agricultural productivity, access to productive assets, and household income are increasing among participating communities (Ara et al., 2024).

### *2.3. Agricultural Development and Poverty Reduction*

It is well established that agricultural development is a key route to reducing poverty in developing nations, where the majority of the population relies on agriculture for income. Expansion in the agricultural sector is highly poverty-alleviating, as it directly benefits the rural population that depends on agriculture to earn a living. Chand (2025) argues that in many developing countries, agricultural growth is much more effective at reducing poverty than non-agricultural growth.

In Nigeria, agricultural development programmes have been geared towards enhancing farmers' productivity, food security, and rural incomes. These programmes are supposed to enhance agricultural production and improve the livelihoods of rural populations by supplying farmers with better seeds, fertilizers, irrigation, and technical expertise. An increase in agricultural productivity enables farmers to earn more money, thereby enhancing their standards of living and allowing them to invest in other forms of livelihood.

Community-based agricultural development programs promote these advantages by promoting mutual action by rural communities. In rural areas, community members can work together to address common developmental issues through farmer cooperatives, community associations, and participatory planning systems. These partnerships can enhance resource management, knowledge sharing, and the strengthening of rural institutions that facilitate sustainable development.

### *2.4. Community Participation in Development Projects*

The idea of community involvement has emerged as a core principle of contemporary development. Participation is the direct contribution of community members to decision-making processes on development projects that impact their lives. It involves identifying community needs, developing plans, implementing projects, and monitoring project outcomes. Sabet and Khaksar (2024) say that participatory development processes enhance local ownership, social capital, and the sustainability of development results. Communities that are actively engaged in development projects are more likely to support project implementation and the maintenance of project infrastructure and services.

Community involvement also contributes to empowerment and social inclusion. Marginalized groups, including women, youth, and smallholder farmers, can have access to decision-making platforms and development resources through participatory development processes. Through this process of empowerment, community members can influence policies and initiatives that will shape their lives (Sebunya & Gichuki, 2024).

Community participation in the context of agricultural development projects can take the form of the formation of farmer groups, shared management of resources, participatory planning workshops, and community monitoring committees. Through these mechanisms, cooperation between community members is promoted, and a greater sense of collective responsibility is fostered in the development process.

### *2.5. Hypothesis Development*

Based on the literature reviewed, community-based agriculture and rural development projects are expected to contribute to poverty reduction by improving agricultural productivity, increasing rural incomes, and strengthening local economic opportunities. Empirical studies have consistently demonstrated the positive impact of agricultural development initiatives on poverty alleviation in rural communities (Badaruddin et al., 2021; Carmen et al., 2022; Eriksson et al., 2021; Sebunya & Gichuki, 2024; Zhou & Kaplanidou, 2018). Therefore, this study hypothesized that (see Figure 1):

**H1:** Community-Based Agriculture Projects have a significant positive influence on poverty reduction in Nigeria.

**H2:** Rural development Projects have a significant positive influence on poverty reduction in Nigeria.

**H3:** Community participation has a significant positive influence on poverty reduction in Nigeria.

**H4:** Community participation significantly moderates the relationship between Community-Based Agriculture and Rural Development Projects and poverty reduction in Nigeria.

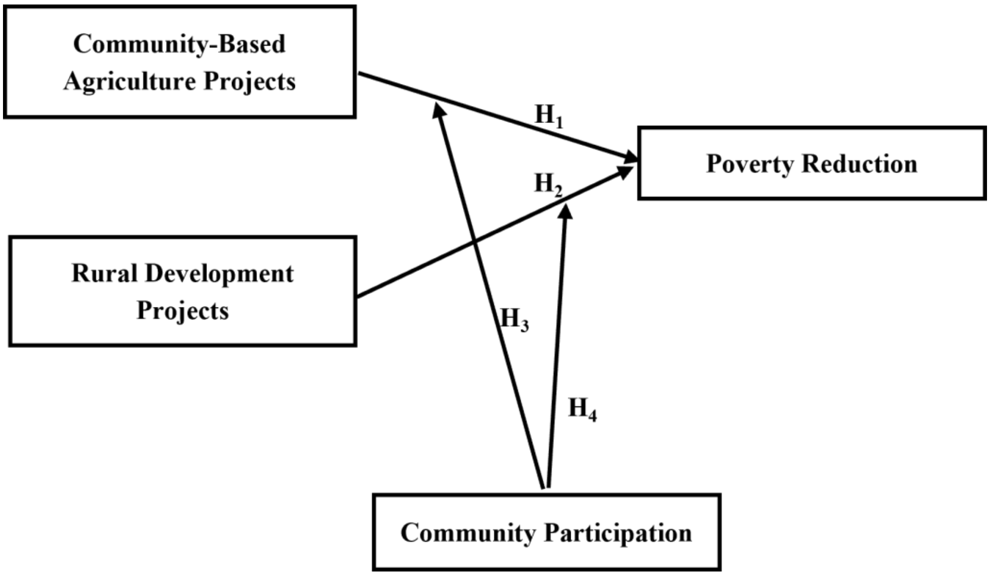


**Figure 1.** Research Framework.

### 3. Methodology

The impact of Community-Based Agriculture and Rural Development Projects (CBARDP) and community participation on poverty reduction in Nigeria was evaluated using a quantitative cross-sectional survey method (CBARDP; Creswell & Creswell, 2017). The target population was limited to rural household heads in the states where the CBARDP was implemented. The sample was obtained through multi-stage stratified random sampling, in which three geopolitical zones (North-West, North-East, South-South) were purposively selected; two states were randomly selected in each; and finally, local government areas were selected based on evidence of being CBARDP beneficiaries. Systematic random sampling was used to select households in the communities.

Based on the SEM rule of 10 respondents per indicator (Hair et al., 2019), a target of 400 questionnaires was set, yielding 385 usable responses, for a response rate of 96.25%. Data was collected through a survey questionnaire that included questions on participant demographics (Section A), and questions related to the 5 point participatory Likert scale (CBAP) Community Based Agriculture Projects, Rural Development Projects (RDP), Community Participation (CP), and Poverty Reduction (PR), with adaptations made from Ara et al. (2024), Nura (2022), Forkuor and Korah (2023), Abubakar (2022), Sabet and Khaksar (2024), Sebunya and Gichuki (2024), Prince et al. (2023), and Jaiyeola and Bayat (2020). Content validity was confirmed through expert review, and the pilot study (n = 40) yielded Cronbach's alpha values exceeding 0.70 for all components (Nunnally, 1978). A summary of the items for each component is presented in Table 1.

**Table 1.** Summary of Construct Measurement Items

| Construct | Items | Sources |
|---|---|---|
| Community-Based Agriculture Projects (CBAP) | 6 | Ara et al. (2024); Nura (2022) |
| Rural Development Projects (RDP) | 6 | Forkuor and Korah (2023); Abubakar (2022) |
| Community Participation (CP) | 6 | Sabet and Khaksar (2024); Sebunya and Gichuki (2024) |
| Poverty Reduction (PR) | 6 | Prince et al. (2023); Jaiyeola and Bayat (2020) |

Note: Questionnaire items adapted from the above-listed authors.

Anderson and Gerbing's (1988) two-step approach was followed in analyzing the data using IBM SPSS AMOS version 26. Measurement model fit was assessed using Confirmatory Factor Analysis (CFA) by examining fit indices via $\chi^2$/df ($\leq$ 3.00), CFI and TLI ($\geq$ 0.90), RMSEA and RMSEA ($\leq$ 0.08), and Composite Reliability (CR$\geq$ 0.70) and Average Variance Extracted (AVE $\geq$ 0.50) and the HTMT ratio (< 0.85) for discriminant validity (Fornell & Larcker, 1981; Hair et al., 2019; Henseler et al., 2015; Hu & Bentler, 1999) and shown in Table 2. Following that, the structural model was the assessment of the direct effect(s) of CBAP and RDP on poverty reduction (H1, H2), the direct effect of CP on poverty reduction (H3), as well as the moderation effect of CP (H4) via multi-group analysis of the moderated model (i.e. constrained and unconstrained groups) via chi-square difference tests ($\Delta\chi^2$; Kline, 2016). Each effect was analyzed via bootstrapping (5,000 resamples, 95% bias-corrected CI; Preacher & Hayes, 2008). To mitigate common method bias, Harman's single-factor test and the Common Latent Factor approach were employed (Podsakoff et al., 2003). Fieldwork commenced upon receiving ethical approval. Informed consent and respondent anonymity were guaranteed.

**Table 2.** Model Fit Indices and Acceptable Thresholds.

| Fit Index | Threshold | Reference |
|---|---|---|
| $\chi^2$/df | $\leq 3.00$ | Hair et al. (2019) |
| CFI | $\geq 0.90$ | Hu & Bentler (1999) |
| TLI | $\geq 0.90$ | Hair et al. (2019) |
| RMSEA | $\leq 0.08$ | Hu & Bentler (1999) |
| SRMR | $\leq 0.08$ | Hair et al. (2019) |
| CR | $\geq 0.70$ | Hair et al. (2019) |
| AVE | $\geq 0.50$ | Fornell and Larcker (1981) |
| HTMT | $< 0.85$ | Henseler et al. (2015) |

Note: fitness indices as recommended by scholars.

## 4. Results

### *4.1. Preliminary Tests: Sampling Adequacy and Common Method Bias*

The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy returned a value of .886, well above the .60 threshold (Kaiser, 1974) and deemed meritorious. This result signifies that the items exhibit specific, compact correlation patterns and that factor analysis is warranted for this data set. Bartlett's Test of Sphericity was significant ($\chi^2 = 6718.151$, df = 276, $p < .001$), indicating that the correlation matrix is not the identity matrix and that the items have sufficient common Variance to warrant factor extraction. Collectively, these results, as shown in Table 3, demonstrate the adequacy of the data's factorability and the appropriateness of the sample for the confirmatory factor analysis and structural equation modelling that follow.

**Table 3.** KMO and Bartlett's Test of Sphericity.

| KMO and Bartlett's Test | | Value |
|---|---|---|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy | | .886 |
| Bartlett's Test of Sphericity | Approx. Chi-Square | 6718.151 |
| | df | 276 |
| | Sig. | .000 |

### *4.2. Harman's Single-Factor Test for Common Method Bias*

To evaluate common method bias, we applied Harman's single-factor test (Table 4). We performed principal components analysis (PCA) without rotation on all items. The first unrotated factor explained 27.992% of the total Variance. Since this number is well below the 50% threshold (Podsakoff et al., 2003), this study does not suffer from common-method bias. The single factor explains a relatively low proportion of the Variance, indicating that the self-report data are not highly contaminated by common method variance, supporting the validity of the measurement model and the structural relationships to be evaluated in subsequent analyses.

**Table 4.** Common Method Bias (CMB).

| Component | Total Eigenvalue | % of Variance | Cumulative % | Extraction Total | Extraction Cumulative % |
|---|---|---|---|---|---|
| 1 | 6.718 | 27.992 | 27.992 | 6.718 | 27.992 |

Note: Extraction Method: Principal Component Analysis.

### *4.3. Reliability Analysis*

Cronbach's alpha coefficient was used to evaluate each construct's reliability. All four constructs showed strong internal consistency, as Table 5 illustrates, with alpha values exceeding Nunnally's (1978) minimum acceptable threshold of 0.70. Rural Development Projects ($\alpha = 0.860$) and

Community Participation (α = 0.834) showed good reliability, whereas Community-Based Agriculture Projects (α = 0.923) and Poverty Reduction (α = 0.889) demonstrated excellent reliability. Since all item-total correlations fell within acceptable bounds, no items were removed during this phase. These findings confirm that the measurement tools have sufficient reliability for further confirmatory factor analysis.

**Table 5.** Reliability Test Results.

| Construct | Items Deleted | No. of Items | Cronbach's Alpha |
|---|---|---|---|
| Community-Based Agriculture Projects (CBAP) | Nil | 6 | 0.923 |
| Rural Development Projects (RDP) | Nil | 6 | 0.860 |
| Community Participation (CP) | Nil | 6 | 0.834 |
| Poverty Reduction (PR) | Nil | 6 | 0.889 |

Note: Cronbach's Alpha was tested using a threshold of 0.7.

### *4.4. Confirmatory Factor Analysis (CFA)*

IBM SPSS AMOS 26 was used to perform a Confirmatory Factor Analysis (CFA) to evaluate the measurement model's psychometric properties. Initially, all 24 items from each of the four constructs were used to test the pooled CFA model. To increase model parsimony and fit, three items (RDP6, CP5, and CP6) were eliminated after modification indices and item loadings were examined. This elimination resulted in a final measurement model with 21 items. Across several indices, the improved measurement model showed respectable goodness-of-fit. All factor loadings were statistically significant and above the suggested 0.50 threshold, and the CFA model fit was satisfactory.

### *4.5. Validity Analysis*

All four constructs satisfied the convergent validity criterion, as shown in Table 6: Composite Reliability (CR) values ranged from 0.907 to 0.925, all surpassing the 0.70 threshold (Hair et al., 2019). More than half of the Variance in each construct is explained by its indicators, as confirmed by the Average Variance Extracted (AVE) values, which varied from 0.622 to 0.725 and were all above the suggested 0.50 criterion (Fornell & Larcker, 1981). Using the Fornell-Larcker criterion, the square root of each construct's AVE (bold diagonal values) was greater than all inter-construct correlations, indicating discriminant validity. Discriminant validity was further confirmed as all constructs' Maximum Shared Variance (MSV) values were less than their matching AVE values.

**Table 6.** Validity Analysis.

| Constructs | CR | AVE | CA_Projects | RD_Projects | C_Participation | P_Reduction |
|---|---|---|---|---|---|---|
| CA_Projects | 0.925 | 0.676 | **0.822** | | | |
| RD_Projects | 0.925 | 0.712 | 0.279 | **0.844** | | |
| C_Participation | 0.913 | 0.725 | 0.087 | 0.120 | **0.851** | |
| P_Reduction | 0.907 | 0.622 | 0.277 | 0.247 | 0.052 | **0.789** |

### *4.6. Structural Equation Modelling (SEM) – Direct Effects*

To test the proposed direct relationships between the predictor constructs and poverty reduction, the structural model was estimated (H1–H3). Figure 2 below shows the structural model's model fitness indices.

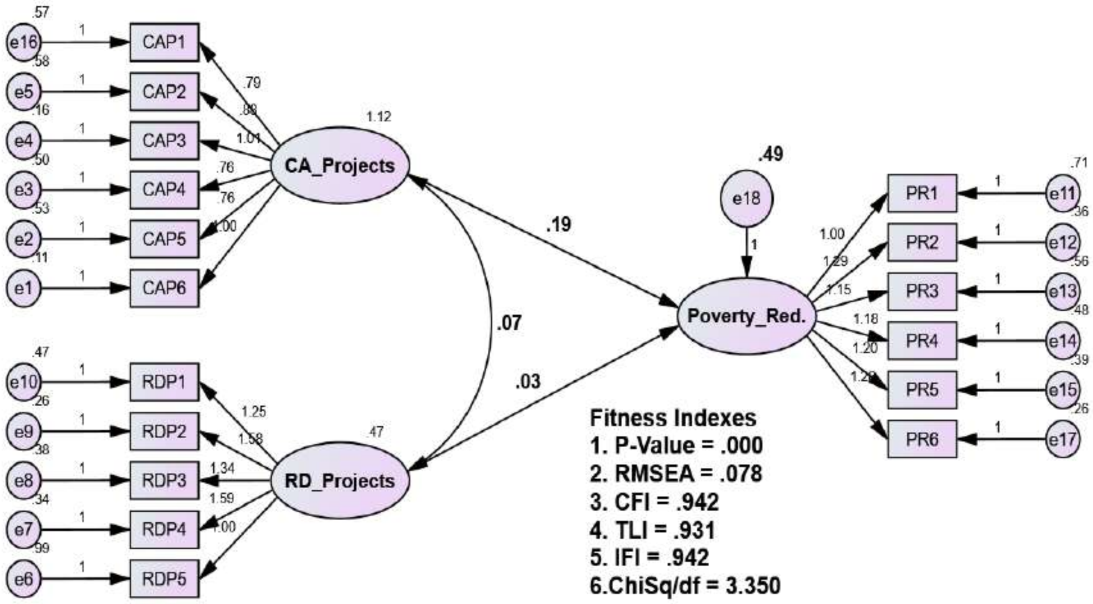


**Figure 2.** Structural Equation Model Fitness Indexes.
**Note:** P-Value = .000; RMSEA = .078; CFI = .942; TLI = .931; IFI = .942; ChiSq/df = 3.350.

The structural model fitness indices indicate an acceptable fit to the data. Good model fit was indicated by the CFI (.942), TLI (.931), and IFI (.942) exceeding the suggested threshold of ≥ 0.90 (Hair et al., 2019; Hu & Bentler, 1999). The RMSEA value suggests a reasonable approximation of the model to the population covariance structure of.078, which falls within the acceptable range of ≤ 0.08. Because chi-square is sensitive to sample size, the $\chi^2$/df ratio of 3.350 is generally accepted in social science research with large samples, even though it is slightly above the strict threshold of ≤ 3.00 (Kline, 2016). Taken as a whole, these indices indicate that the structural model adequately captures the observed data.

The hypothesis that Community-Based Agriculture Projects (CBAP) have a positive impact on poverty reduction (H1) is supported, as Table 7 illustrates. Higher participation in community-based agricultural projects is associated with significant reductions in poverty among rural communities, as indicated by a statistically significant standardised path coefficient (β = 0.189, S.E. = 0.038, CR = 4.944, p < .001). Although this effect is small, it is accurately calculated and consistent across bootstrapped confidence intervals, indicating that improvements in agricultural access, inputs, and farmer mobilisation through CBAP significantly reduce rural poverty.

**Table 7.** Hypotheses Testing – Direct Effects

| Relationship | Estimate (β) | S.E. | CR. | p-value | Decision |
|---|---|---|---|---|---|
| Poverty Reduction ← CA_Projects | .189 | .038 | 4.944 | *** | Supported (H1) |
| Poverty Reduction ← RD_Projects | .033 | .057 | .570 | .569 | Not Supported (H2) |

*** p < .001.

On the other hand, there is no evidence to support the hypothesis that Rural Development Projects (RDP) directly lower poverty (H2). The path coefficient (β = 0.033, S.E. = 0.057, CR = 0.570, p = .569) was small and not statistically significant. This result implies that RDP does not directly reduce poverty in a statistically significant way. This result does not necessarily mean that RDP is ineffective; rather, it suggests that other enabling conditions, such as the degree of community participation, examined in the moderation analysis below, may be necessary for the benefits of rural development infrastructure and services in reducing poverty.

### *4.7. Moderation Analysis: The Role of Community Participation*

A moderation model was estimated using standardised z-scores for all predictor, moderator, and interaction terms to test H3 (the direct effect of community participation on poverty reduction) and H4 (the moderating role of community participation on the CBARDP–poverty reduction relationship). The interaction terms were derived from the products of standardised community participation scores with standardised CBAP and RDP scores, respectively. Figure 3 shows the moderation model.

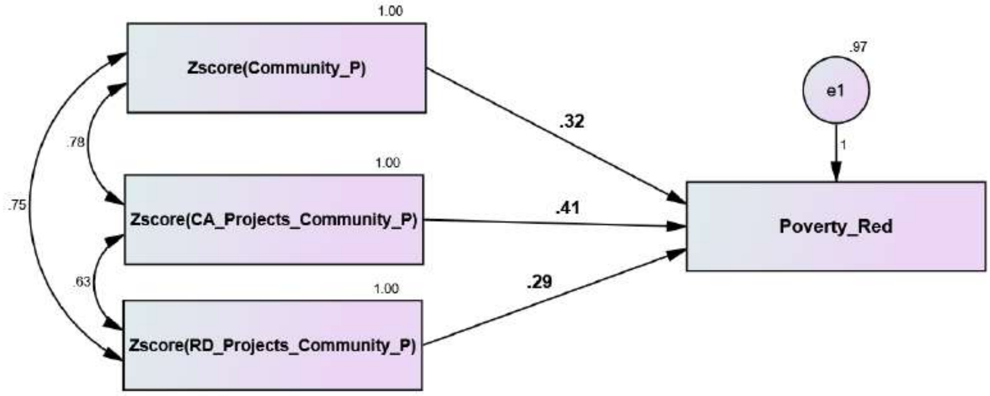


**Figure 3.** Moderation Model.

The moderation model accounted for 47% of the Variance in poverty reduction ($R^2 = .47$), indicating significant explanatory power. The direct effect of community participation (H3) on poverty reduction was positive and significant ($\beta = .237$), indicating that communities with higher levels of active engagement in development processes achieve more substantial poverty reduction outcomes (see Table 8). This result supports H3 and aligns with the idea that participatory governance makes development more effective.

**Table 8.** Moderation Path Coefficients.

| Relationship | Label | Standardized Estimate (β) | Decision |
|---|---|---|---|
| Poverty Reduction ← Community Participation (H3) | Zscore(Community_P | .237 | Supported (H3) |
| Poverty Reduction ← CA_Projects × Community Participation (H4a) | Zscore(CA_Projects_Community_P) | .304 | Supported (H4) |
| Poverty Reduction ← RD_Projects × Community Participation (H4b) | Zscore(RD_Projects_Community_P) | .215 | Supported (H4) |

Note: Standardized coefficients are reported. The direct effects in Table 8 include standard errors and p-values estimated using maximum likelihood estimation. Interaction effects were estimated using standardized product terms.

The interaction term between community participation and Community-Based Agriculture Projects (CBAP × CP) produced the most robust coefficient in the moderation model ($\beta = .304$), signifying that community participation substantially enhances the poverty-reduction impact of CBAP. The result suggests that CBAP is more effective at reducing poverty in communities with greater community involvement. This interaction makes agricultural interventions more effective.

The interaction term between Rural Development Projects and community participation (RDP × CP) was also positive and significant ($\beta = .215$). This finding is especially important because RDP did not have a statistically significant direct effect on reducing poverty (H2 not supported). The substantial moderation effect ($\beta = .215$) indicates that rural development initiatives yield poverty-alleviation benefits, contingent on active community participation. If people in the community do not get involved, the benefits of rural development infrastructure and services may not translate into real reductions in poverty. It seems that community participation is essential to making the RDP work. It connects development investments to real improvements in household welfare. This result completely backs up H4.

## 5. Discussion

### *5.1. Direct Effects of CBARDP on Poverty Reduction*

The discovery that Community-Based Agriculture Projects (CBAP) significantly forecast poverty reduction (β = .189, $p < .001$) aligns with existing empirical literature illustrating the poverty-reducing efficacy of agricultural interventions in rural Nigeria and sub-Saharan Africa (Ara et al., 2024; Chand, 2025). CBARDP's agricultural projects, such as providing better inputs, developing farmer cooperatives, and giving farmers access to extension services, directly address some of the main structural problems that rural smallholders face in making a living. CBAP helps families cross the line between subsistence and prosperity by increasing farm productivity and income. This process allows them to invest in education and healthcare and build up productive assets over time. This finding aligns with those of Badaruddin et al. (2021), who found that community-driven agricultural empowerment enhances household welfare among rural populations in developing contexts.

The insignificant direct effect of Rural Development Projects on poverty reduction (β = .033, p = .569) offers a more complex perspective. This result may seem strange at first because there is substantial evidence and policy support for investing in rural infrastructure to reduce poverty. Nonetheless, this finding is not entirely at odds with the existing literature. Forkuor and Korah (2023) observe that the conversion of rural development investments into enhanced livelihoods is frequently influenced by local governance capacity, social cohesion, and community ownership of project outcomes. In the Nigerian context, implementation gaps, limited community ownership, lack of maintenance, and low participation constrain their contribution to household welfare (Abubakar, 2022). The current observation indicates that, unless the facilitating circumstances that community participation offers, RDP benefits are not consistently delivered to vulnerable households.

### *5.2. Community Participation as a Direct Driver of Poverty Reduction*

The direct impact of community participation on poverty reduction (=.237) contributes to a body of evidence increasingly treating participation as a development outcome rather than a device to achieve an outcome. Active communities in the planning, implementation, and monitoring of developmental activities build social capital, institutional capacity, and collective agency, which, in turn, will contribute to reducing poverty (Portes, 1998; Sabet & Khaksar, 2024). Making active also reinforces accountability structures, minimizes resource leaks, and ensures that development gains are channeled to vulnerable members of the community (Uzorka et al., 2024). All these processes will lead to increased household welfare, regardless of the nature of the projects undertaken.

These findings are echoed by Sebunya and Gichuki (2024), who found that communities with high levels of participation in rural development planning exhibit greater long-term socio-economic benefits. The implication is that participation should not be seen merely as a tool for enhancing project delivery but as an objective of development itself, one that establishes the institutional bases for permanent poverty reduction.

### *5.3. The Moderating Role of Community Participation*

The findings of the moderation give the most theoretically significant results of this paper. H4a was confirmed by the significant poverty-reduction impact of CBAP when carried out by the community (.304). This synergistic impact is consistent with the theory of participatory development, which holds that community ownership can change the utilization and sustainability of agricultural interventions (Dushkova & Ivlieva, 2024). By involving rural households in the design and implementation of projects, agricultural technologies and inputs are more likely to be adopted, sustained, and customized to local ecological conditions, thereby maximizing productivity benefits and poverty reduction.

The most practically relevant finding is the moderation of the impact of community participation on the poverty reduction introduced by RDP (.215). The situation where RDP had no substantial direct impact but was found to be effective with moderation through community participation highlights the importance of participatory mechanisms as essential enabling factors for infrastructure-oriented development interventions. The result is in line with the general literature on community-driven development, which underscores that investments in physical infrastructure can yield socio-economic returns only when supported by robust community governance and ownership systems (Awoyemi & Oke, 2024; Mehedi Hasan et al., 2026). In the Nigerian case, this implies that the standard problem of the so-called white elephant rural infrastructure projects, constructed but never used or serviced, can be resolved by attempting to systematize investment in the capacity to engage communities.

The overall $R^2$ of.47 in the moderation model implies that the interactions among CBAP, RDP, community participation, and their interaction terms explain 47 percent of the poverty reduction in the participating communities. This result shows a significant explanatory power of a parsimonious three-predictor framework, indicating that the CBARDP framework, coupled with authentic community involvement, is a potent tool for addressing rural poverty in Nigeria.

## 6. Policy Implications

The impact of CBAP is very high, confirming that community-based agricultural programming must remain a priority in Nigeria's anti-poverty plan. Farmers' Cooperative Policies that support the development of cooperatives and improve access to better inputs and agricultural extension services should be increased and maintained.

Secondly, the contingent character of the RDP effects on levels of community participation implies that mobilization of rural populations, capacity building and participatory governance programmes should be combined with rural infrastructure investments. Isolated infrastructure undertakings, unlinked to community ownership systems, will not yield the best results in reducing poverty.

Third, community participation should be institutionalized as a required component of CBARDP programming by government agencies and development partners, rather than being optional or symbolic. The moderation effects in this study are motivated by meaningful participation, that is, real decision-making power, open resource management, and community-level monitoring. Conversely, tokenistic involvement is unlikely to yield such synergistic benefits. Finally, because it is significant to participate as a direct participant and moderator in poverty reduction, social mobilization, civic education, and community-level governance, these activities should be reflected in the budget as development expenditures, not administrative overhead.

## 7. Conclusion

This paper uses the Community-Based Agriculture and Rural Development Projects (CBARDP) as the determinant of poverty reduction in Nigeria and community participation as the moderating variable. The study applied SEM to 385 rural household heads across various geopolitical areas and found that Community-Based Agriculture Projects (CBAP) had a significant positive direct impact on poverty reduction. In contrast, Rural Development Projects (RDP) did not. It was noted that community participation was a direct positive factor towards reducing poverty and, most importantly, a strong moderator that enhanced the poverty-reduction impacts of both CBAP and RDP. This may reflect that RDP initiatives often lack localized targeting, unlike CBAP, which are inherently participatory. The moderation model explained 47 percent of the variation in poverty reduction and confirmed the results' feasibility. Our findings empirically validate the Asset-Based Community Development theory by demonstrating that participation amplifies returns on project investments. Our results challenge top-down, supply-driven rural development models and advocate for deliberate, funded participatory mechanisms as a non-negotiable component of project design.

## 8. Limitations and Further Studies

First, it is more difficult to determine causal correlations between the studied variables when using a cross-sectional research methodology. Future longitudinal studies are necessary to investigate how the links between Community-Based Agriculture Projects, Rural Development Projects, community engagement, and poverty reduction change over time, even if the structural model has strong explanatory power.

Second, the study concentrated on particular Nigerian geopolitical zones. Despite the fact that these zones offer insightful information about rural development interventions, care should be used when extrapolating the results to the entire nation due to variations in institutional capability, program implementation, and socioeconomic factors.

Third, future research should investigate whether various aspects of community participation, such as participation in project appraisal, planning, implementation, monitoring, and financial decision-making, produce different moderating effects on outcomes related to poverty reduction.

Finally, researchers should adopt mixed-methods and process-tracing approaches across various agro-ecological zones and sub-Saharan African contexts to better understand the institutional and behavioral mechanisms through which community participation affects the efficacy of Community-Based Agriculture and Rural Development Projects.

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### Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CBARDP | Community-Based Agriculture and Rural Development Projects |
| CBAP | Community-Based Agriculture Projects |
| RDP | Rural Development Projects |
| CP | Community Participation |
| PR | Poverty Reduction |
| SEM | Structural Equation Modelling |
| AMOS | Analysis of Moment Structures (IBM SPSS AMOS) |
| SPSS | Statistical Package for the Social Sciences |
| CFA | Confirmatory Factor Analysis |
| PCA | Principal Component Analysis |
| KMO | Kaiser–Meyer–Olkin Measure of Sampling Adequacy |
| CMB | Common Method Bias |
| CR | Composite Reliability *(also Critical Ratio in SEM path output—see note below)* |
| AVE | Average Variance Extracted |
| HTMT | Heterotrait–Monotrait Ratio of Correlations |
| SRMR | Standardized Root Mean Square Residual |
| RMSEA | Root Mean Square Error of Approximation |
| CFI | Comparative Fit Index |
| TLI | Tucker–Lewis Index |
| IFI | Incremental Fit Index |
| MSV | Maximum Shared Variance |
| $\chi^2$ | Chi-Square Statistic |
| Df | Degrees of Freedom |
| S.E. | Standard Error |
| B | Standardized Regression Coefficient (Beta Coefficient) |
| $R^2$ | Coefficient of Determination (Explained Variance) |
| Sig. | Significance Value (p-value) |
| H1–H4 | Research Hypotheses 1–4 |
| z-score | Standardized Score |

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*Article*

# Women's Aspirations for Income Opportunities in Indonesian Oil Palm Villages

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**Abstract:** The expansion of male-dominated cash crops marginalizes women in the economic value chain, especially in Indonesia's palm oil industry. However, research on pathways for women's economic integration remains limited. This study addresses this gap through an exploratory empirical investigation using primary data from 65 women from selected villages in Jambi, a key province for oil palm cultivation in Indonesia. We explore women's work aspirations in general and specifically with regard to beekeeping, an activity that may represent a complementary livelihood strategy with the potential to contribute to economic, social, and environmental sustainability. Findings show that although household income rose due to palm oil, women nevertheless aspire to work, indicating a clear demand for economic participation and agency. We cluster their aspired professions into "Traders," "Education and health-oriented aspirations," and "Other aspirations." The majority of women are open to beekeeping activities, and those who are not raise concerns that could largely be addressed through information, training, and the use of stingless bees. Further research is needed to understand what this means in terms of market potential and adoption rates. Our results offer critical insights for policymakers and researchers working toward more equitable and sustainable smallholder agricultural value chains as we identify concrete entry points, such as targeted training and the promotion of low-maintenance activities like stingless beekeeping, for diversifying women's income opportunities in oil palm-dominated landscapes.

**Keywords:** gender; smallholders; palm oil; beekeeping; rural development; Indonesia

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## 1. Introduction

The expansion of oil palm plantations across Indonesia during the last few decades has led to fundamental land use changes (Qaim et al., 2020). While the boom of monoculture oil palm cultivation yields increased income for farm households, there are numerous, serious downsides. First, from an environmental perspective, the expansion of oil palm plantations comes at the cost of destroying forestland, and a single crop cultivation depletes biodiversity (Morgans et al., 2018). Second, from a socioeconomic perspective, the land use change towards oil palm cultivation from previous crops such as rubber, cacao, or coffee tends to exclude women (Chrisendo et al., 2020; Mehraban et al., 2022). The palm oil industry is predominantly male-dominated, and despite the critical importance of gender-related concerns in this sector, they have received minimal attention thus far. Although women were previously involved, for example, in rubber cultivation, they now tend to have little access or control over oil palm earnings, as men are the ones receiving payment when the fresh fruit bunches are harvested (Araya, 2019). In general, women have been shown to suffer structural barriers in rural settings, particularly when accessing productive assets (Doss et al., 2018; Schneider et al., 2024). The exclusion of women from what is often the only source of income, such as oil palm cultivation, can lead to gender-specific differences in the distribution of resources within the household, which in turn are of fundamental importance for the economic participation of women, leading to higher dependency on men (Etuah et al., 2020). This exclusion has been shown to result in women having lower control over the household's finances and thus decision-making power within the household, resulting in lower self-determination (Doss, 2013; Meinzen-Dick et al., 2011; Julia & White, 2013). Furthermore, women with their own income sources have been shown to be more likely to spend their income on common goods for the household, such as cooking more nutritious meals (Sangwan & Kumar, 2021).

Although gender equality and women's empowerment[1] are crucial factors for sustainable development, particularly among rural women (Shenbei et al., 2023), to date it is not clear what sustainable economic integration of women in oil palm-growing villages could look like. If women were to take an alternative income opportunity complementary to oil palm cultivation, then they would likely increase their resilience, financial agency[2], autonomy, and self-esteem. Chrisendo et al. (2020) show that female off-farm labor contributes positively to household nutrition. However, it remains unclear whether rural women desire alternative income sources, and if so, what types of activities they prefer and their suitability given the circumstances. Additionally, it is important to discuss what barriers prevent them from pursuing these activities. Against the background of gender disparities in male-dominated cash crop landscapes, this understanding becomes pivotal to ensure the design of targeted interventions and activities. If such an activity was also ecologically beneficial, there is potential for it to further incentivize pro-environmental behavior.

If women wished for economic activities, ideally such an activity would cover all three pillars of sustainability – i.e. social, economic, and environmental –in order to address the current adverse outcomes of oil palm cultivation. One promising activity in this context is beekeeping, as it can function complementarily to oil palm cultivation and can thus be seen as a form of on-farm diversification. Indeed, on-farm diversification has been shown to particularly benefit rural women in terms of increased food security and empowerment (Hegazi & Seyuba, 2024). Enabling women in oil palm cultivating villages to equip themselves with meliponiculture starter-sets could provide ecosystem services through pollination and incentives for preserving natural forests (environmental sustainability), additional income (economic sustainability), as well as agency and capacity building (social sustainability) for the women.

While many activities could foster social and economic sustainability, beekeeping is particularly interesting because of its potential to also drive environmental sustainability in an industry in need of pro-environmental incentivization. Monoculture oil palm has been associated with adverse environmental consequences, such as deforestation and biodiversity loss (Krishna et al., 2017b; Kubitza et al., 2018; Qaim et al., 2020). As beekeepers, women and the community can understand the services of the environment, i.e., that the forest is needed for the bees to produce the honey. This change of economic incentivization can, along with environmental education and awareness, function as a strong mechanism to protect forest area, while the bees themselves will enrich biodiversity. Beekeeping holds further potential to be a promising economic activity as it can be complementary to oil palm cultivation and does not need much land. It does not require much time from the beekeeper, thus enabling women to still fulfill other duties. Further, the produced honey can be marketed by the women at the local market and beyond, as honey can be stored for a long time.

Against this backdrop, the objective of this study is to conduct an exploratory, empirical investigation into women's preferences for income generation in rural Indonesia. For this purpose, we pose three research questions (RQ): (1) If any, which income generation activities are attractive for women adjacent to the palm oil industry? (2) How can we cluster women based on their aspired activities, and how can these clusters be described? And finally, (3) Is there an interest in beekeeping activities, and if not, what are the concerns? Thus, our strategy to investigate the women's preferences is twofold. We want to elicit and categorize the aspirations from the women (RQ 1 & 2); and we want to hear their opinions on beekeeping, an economic activity we derived from the literature and through conversations with local counterparts as potentially welfare-increasing (RQ 3).

Given the limited prior research on women's economic preferences in oil palm landscapes, this study takes an exploratory approach. The focus on beekeeping as a potential income activity did not emerge from the literature alone. During preliminary field visits to Jambi province, the first author encountered anecdotal evidence from local stakeholders, e.g., through conversations with representatives of *Rumah Madu* (Indonesian for Honey House), a local honey nongovernmental organization, suggesting that beekeeping could be a viable and desirable activity for women in oil palm cultivating communities. These field-based observations motivated a subsequent literature review, which confirmed beekeeping's potential as a sustainable income source. Together, this informed the design of an exploratory study. To approach our research questions, we therefore rely on survey interviews conducted with 65 women from oil palm cultivating villages in Jambi, Indonesia. The province of Jambi is among the world's leading regions in oil palm cultivation, with

[1] We define empowerment according to Kabeer (1999) as a process of change of "power over" that involves three interrelated dimensions of resources, agency, and achievements.

[2] In this study, we understand agency according to Malapit et al. (2019) and Kabeer (1999) as "the capacity to define one's own goals and make strategic choices to pursue these goals, especially in contexts where this was not possible before."

livelihoods heavily reliant on the crop (Qaim et al., 2020). We employ a cluster analysis to categorize the women's aspirations. To the best of our knowledge, we are the first to investigate women's attitudes and wishes for economic integration within a landscape of male-dominated cash crops. Our results provide insights into the socio-economic dynamics of oil palm expansion. By presenting women's aspirations, we offer insights for policymakers and researchers working towards making oil palm value chains more resilient and sustainable.

The remainder of this paper is organized as follows: Section 2 provides background information. Section 3 introduces the methods and materials utilized in this study. In Section 4, we present and discuss the results, followed by the conclusion in Section 5.

## 2. Background

Women in rural regions of the Global South face structural disadvantages that limit their economic participation and agency (Sharma & Das, 2021). These challenges are particularly pronounced in agricultural landscapes dominated by male-dominated cash crops, where women's roles have been systematically marginalized. Yet despite the scale of this exclusion, women in oil palm cultivating communities remain an understudied group, rarely consulted about their own economic aspirations or needs. Oil palm cultivation in Indonesia exemplifies this dynamic, as its rapid expansion has deepened gender inequalities while simultaneously offering limited pathways for women's economic inclusion. Against this backdrop, complementary and sustainable income activities emerge as a promising avenue to address both social and environmental challenges at once. Beekeeping, in particular, stands out as such an activity: it requires little land and time, entails low upfront costs, and can generate income through honey and other bee products (Chanthayod et al., 2017). Moreover, through pollination services, beekeeping can simultaneously contribute to environmental sustainability in landscapes threatened by monoculture expansion (Kumsa et al., 2021).

### *2.1. Rural Regions and Gender Specific Challenges*

Worldwide, women hold an integral role in the rural agricultural sector, yet often with considerable disadvantages compared to men, referred to as the gender gap. Women are more likely to be food insecure (FAO et al., 2026). Further, as producers, they are more likely to lack access to farm inputs, financial and educational services, as well as technologies (FAO, 2021). Women also tend to have more household responsibilities than men do and tend to take over the majority of childcare (FAO, 2011; UNDP, 2016). However, if rural women are able to access services and productive resources and get economic opportunities, there are considerable positive economic and overall welfare effects (FAO, 2021). Therefore, closing the gender gap, especially within the rural agricultural sector, is of integral importance for the global development agenda, i.e., the Sustainable Development Goals, hereinafter SDG, see SDG 5 "Gender Equality."

In many cultivation systems, women take on an active role in a variety of farm-related activities—from seeding to marketing (Piedrahita et al., 2023; Satyavathi et al., 2010) —which ensures economic inclusion. Rural regions in the Global South typically have little infrastructure and, with that, limited economic opportunities (Mu & van de Walle, 2011; Pinstrup-Andersen & Shimokawa, 2006). Agriculture is the dominant economic activity, as either a smallholder farmer or farm laborer (Adegbite & Machethe, 2020; Rapsomanikis, 2015). When women have a lesser or more disadvantaged role within the rural agricultural sector, this leaves limited opportunities for economic inclusion of women. Markets in rural regions are easily saturated due to the limited income and thus purchasing power of households within the villages. So many agents can only undertake typical service occupations for the direct community—such as selling food—as supply would quickly surpass demand. Engaging in other entrepreneurial activities can be challenging due to potentially high upfront costs paired with limited access to credit markets. Finding off-farm employment in larger cities can furthermore be challenging due to limited infrastructure (and with that high travelling costs and long travelling times), with questionable welfare benefits for the women who also have a pivotal role within the household. Importantly, women's livelihood choices are not determined solely by the availability or profitability of economic activities. They are also shaped by gendered access to productive assets, financial services, information, mobility, and time, as well as by responsibilities within the household (Quisumbing et al., 2014; Doss et al., 2018). From an empowerment perspective, economic opportunities are therefore particularly relevant when they expand women's capacity to make meaningful livelihood choices and exercise control over the resulting income (Kabeer, 1999; Doss, 2013).

### *2.2. Oil Palm and Gender Roles*

While oil palm cultivation has increased overall welfare, the role of women has changed with its expansion. The global demand for palm oil increased starkly over the past decades (Qaim et al., 2020). The global area utilized for oil palm quadrupled from the 1980s to 2018, from less than 5 million hectares to more than 20 million hectares (Qaim et al., 2020). The majority of the land expansion took place in Indonesia and Malaysia, with exports from these two countries now accounting for almost 85% of the globally traded palm oil (Qaim et al., 2020). The expansion of oil palm was shown to have driven rural development overall (Qaim et al., 2020) and in particular food security (Tabe-Ojong Jr. et al., 2023), improved household welfare (Mehraban et al., 2021), and enhanced nutrition (Chrisendo et al., 2022). Furthermore, oil palm cultivation was shown to be positively associated with human capital development (Tabe-Ojong Jr. & Molua, 2023). Despite these gains, the oil palm expansion comes with serious environmental and social costs (Qaim et al., 2020). The expansion of farmland to cultivate oil palm threatens forestland and decreases forest area, while the expansion of mono-culture threatens biodiversity. From a social perspective, oil palm cultivation is a predominantly male industry (Mehraban et al., 2022). The continuous expansion of farmland for oil palm cultivation translates into higher labor demand, primarily for men (Kubitza et al., 2023). This is largely due to the higher physical demand that oil palm cultivation requires as well as the overall lower labor intensity compared to previously cultivated crops such as cacao or rubber (Chrisendo et al., 2020; Etuah et al., 2020; Mehraban et al., 2022).

The gendered shift in labor demand associated with the oil palm expansion can result in negative consequences for females in oil palm households, such as lower control over finances, lower agency or decision-making power within the household (Elmhirst et al., 2017; Morgan, 2017). Women's participation in income-generating activities does not, however, automatically translate into greater agency, as household members may differ in their ability to control how income is used (Kabeer, 1999; Doss, 2013). Evidence from different contexts suggests that women's control over resources can influence household expenditure patterns and improve investments in children's nutrition, health, and education (Duflo, 2003; Quisumbing & Maluccio, 2003). In the Philippines, for example, Salazar and Quisumbing (2009) show that women's participation in household financial decision-making is associated with household welfare. Consequently, economic activities may be particularly valuable when they not only generate additional household income but also enable women to exercise control over the income generated.

### *2.3. Beekeeping*

The positive economic development through oil palm cultivation, expressed in the substantial reduction of Indonesia's poverty line, has contributed to the achievement of important development goals, particularly within rural contexts (Qaim et al., 2020). However, the economic exclusion of women is an adverse side effect, which urgently needs to be addressed to foster economic participation in the mid and long run. Against this background, complementary livelihood activities may offer a pathway to women's economic participation, particularly when they are accessible under prevailing constraints on land, capital, mobility, and time. Beekeeping has been identified before as a sustainable economic activity for smallholders (Chanthayod et al., 2017), as it does not require much time or land, has low upfront costs, and potentially creates positive synergies with the cultivated crops through pollination.

Limited empirical evidence suggests that beekeeping offers economic opportunities and can be welfare-increasing for (poor) smallholder farmers (Amuko et al., 2023; Amulen et al., 2019; Berem et al., 2010; Carroll & Kinsella, 2013; Wagner et al., 2019; Mushonga et al., 2019; Otim et al., 2018; Thomas & Tounkara, 2020), especially for marginalized groups (C. Schouten et al., 2019). Beekeeping can increase income and food security of households through the production of honey, beeswax, propolis (e.g., as cream for healing wounds), and royal jelly used as an enhancer for health and beauty (Berem et al., 2010; Krell, 1996). Grüter (2020) presents an insightful overview of stingless bees[3] and their longstanding cultivation among indigenous groups around the world for both their products (similar to the one mentioned above) as well as their cultural, religious, and healing value stemming from the bees themselves and their products. Stingless bees are well known in Southeast Asia (Chantawannakul et al., 2018), with more than 40 stingless bee species recorded alone in Indonesia (Gratzer et al., 2019; Kahono et al., 2018). Timberlake et al. (2026) show how pollination services of stingless bees can support nutrition and income of vulnerable communities.

Furthermore, there is limited empirical evidence on various environmental benefits, such as the positive impact of bees themselves on the net environmental benefits of food through their pollination activities (Sillman et al., 2021), as well as the improved valuation of ecosystem services and pro-environmental behavior of beekeepers (Chanthayod et al., 2017; Kumsa et al., 2021). This could be of special importance in this study context: Especially when oil palm villages are close to the periphery of the tropical rainforest, which is threatened by deforestation for oil palm expansion (Harianja et al., 2023), bees might function as a strong incentive to keep the forest and function as ambassadors to value ecosystem services. There is empirical evidence of changed attitudes and

3 Stingless bees produce honey just like honeybees (who can sting).

behaviors of rural beekeepers. Kumsa et al. (2021), for example, systematically assess the contribution of traditional beekeeping to maintaining agrobiodiversity among rural communities in Ethiopia. Compared to non-beekeepers, they find that beekeepers show more pro-environmental behavior—for example by storing more residues of trees and gardening for their beekeeping activities—are less likely to expand crop production, and have a higher number of floral species in their home-garden. Indeed, Patel et al. (2021) argue that bees play a central role in achieving the SDGs, particularly SDG 2 (food security) and SDG 13 (climate action) and at least 30 of the SDG targets. However, when considering the case of women from oil palm households becoming beekeepers, we can add—as a minimum—contributions to SDG 1 (No Poverty) and SDG 5 (Gender Equality).

## 3. Materials and Methods

### *3.1. Study Site and Data Collection*

This study utilizes primary data collected from September 2022 until March 2023 throughout the Indonesian province of Jambi by trained, local enumerators. The province of Jambi provides an ideal setting for this study, given that smallholders manage 40% of all oil palm plantations (Apriani et al., 2020; Euler et al., 2016). Moreover, the local livelihoods are highly reliant on oil palm cultivation (Qaim et al., 2020), which has played a pivotal role in reducing the national poverty line (Gatto et al., 2017). To ensure targeted and comprehensive data, enumerators specifically focused on women living in oil palm cultivating villages. The study formed part of a larger data-collection effort conducted in Jambi province. The study villages were randomly selected following the sampling procedure outlined in Reich et al. (2026). Their multi-stage procedure first identified the largest oil palm cultivating regencies (kabupaten) within Jambi province, following Krishna et al. (2017a), from which two regencies were randomly selected. Within each regency, four districts were randomly selected, and within each district, two villages were randomly selected. Within these villages, women were randomly approached and asked whether they would be interested in participating in a survey on women's economic role in oil palm cultivating villages. As no complete individual-level sampling frame of eligible women was available, the respondent sample is best characterized as a convenience sample within randomly selected villages.

The interviews then took place either in public gathering spaces or within the participants' homes, allowing for flexibility and comfort. None of the questions were mandatory for participants to answer, and their participation could be withdrawn at any time throughout the interview. The questions were partly formulated as open-ended, allowing women to express their thoughts in their own words. The complete questionnaire can be accessed in Appendix B. The interviews were held in Bahasa Indonesia and lasted, on average, 15 minutes. The interviews were transcribed verbatim. In response to the open-ended question, women were free to name their preferred economic activity in their own words; no predefined list of response options was provided, and more than one answer per respondent was not possible. Each economic activity was assigned to one of seven categories (Administration, Farming, Sales, Services, Social, Nothing, Undecided). Two researchers performed categorization independently, with disagreements resolved through discussion. Interviews were conducted in Bahasa Indonesia and subsequently translated into English by one researcher, with a second researcher reviewing the translations for consistency.

In order to identify patterns within the women's preferences, we first asked the women what kind of work they would like to do with their available resources and skills. Each woman was asked to reflect on the skills she possessed and the resources available to her within the context of her community and household. These questions were intentionally open-ended, ensuring that responses were not confined to predefined categories but instead reflected the diverse aspirations among the women. Through this open-ended approach, we sought to capture the depth and variety of their preferences.

In addition to the open-ended question on preferred economic activities, women were also asked whether they would be open to working with bees and honey production, followed by an open-ended follow-up question asking them to explain their reasoning. Two researchers independently categorized the reasons given by women who indicated hesitancy or opposition into thematic groups, with disagreements resolved through discussion, following the same procedure applied to the economic activity categorization described above.

### *3.2. Cluster Analysis*

We employ a cluster analysis, a technique that is widely accepted for organizing homogeneous subject groups and is commonly employed in market segmentation analysis (e.g., Calvo-Porral & Lévy-Mangin, 2018; Rojas-Rivas et al., 2020). Additionally, it has proven valuable in studying specific population groups, such as farmers (Bruns et al., 2022; Netshipale et al., 2022). All statistical analyses were performed using Stata 15.

In the next step, we grouped their responses into subgroups e.g., grocery selling into Sales, or horticulture into Farming. We present the statements with the subgroup assigned by us in Table A1. The remaining variables for our cluster analysis are thus Administration, Farming, Nothing, Sales, Services, Social, and Undecided. While Mooi et al. (2018) recommend at least ten times as many observations as cluster variables, our sample (N = 65) falls marginally short of this threshold for seven variables (N = 70). Given the exploratory nature of this study, we proceed with the analysis while acknowledging this as a limitation. Our sample consists of 65 women. To test the variables for collinearity, we perform a pairwise correlation estimation. All variables correlate well below the suggested threshold of 0.9 and are thus suitable for the analysis (Mooi et al., 2018).

Based on Mooi et al. (2018), we utilize a hierarchical clustering method, which is considered suitable for sample sizes below 500 respondents (Gunarathne et al., 2017; Kühl et al., 2017). Specifically, we employ Ward's linkage algorithm to group subjects in a manner that minimizes the increase in total variance within the clusters while ensuring the construction of homogeneous clusters with roughly equal membership (Mooi et al., 2018).

Correlations among the clustering variables were generally weak, limiting the influence of redundant information on the clustering solution. Because all clustering variables were binary, extreme values outside the predefined response range were not possible. We subsequently characterized the resulting clusters by descriptively comparing the prevalence of the different aspirations across groups.

We created seven dummy variables for the responses of the women. Agreement with the economic activity is coded as 1 and rejection as 0 so that a general rejection of all economic activities can also be represented. However, as they have many negative matches compared to positive matches, subjects may appear similar. To address this issue, Mooi et al. (2018) propose the Jaccard coefficient to calculate the distance, which does not consider negative agreement between respondents. In the context of our research endeavor, this is the most reasonable interpretation of similarities between sample members. The same procedure for dummy variable clustering of our data structure is generally suggested (see, for example, Everitt et al., 2011, or Kaufman & Rousseeuw, 2009).

Several criteria can be employed for determining the number of clusters in a dataset. One of the most prominent is the Duda-Hart Index. In Table 1, the Duda-Hart Index (Je(2)/Je(1)) is highest for the two-cluster solution, while the modified Duda-Hart Index (pseudo T-squared) is minimized for a three-cluster solution. Instead of selecting only two clusters, we opt for three clusters, as it is the more practical solution, which provides interpretable and meaningful results and fits our data better. Determining the correct number of clusters is thus a result of thorough analysis but also a combination of manageability, context, and practicability (Mooi et al., 2018). Beyond statistical fit, working with seven separate activity categories would result in groupings that are too granular and numerous to be practically meaningful for policy purposes. The cluster analysis addresses this by consolidating the seven categories into three broader, statistically coherent profiles (Traders, Education and health-oriented aspirations, other aspirations), allowing us to characterize distinct groups of women rather than treating each of the seven activity categories separately. This is particularly relevant from a policy perspective, as interventions can be tailored to these three broader profiles rather than to seven narrowly defined activity categories.

**Table 1.** Determination of Cluster Size by Duda-Hart.

| Number of clusters | Je(2)/Je(1) | Pseudo T-squared |
|---|---|---|
| 1 | 0.5995 | 42.08 |
| 2 | 0.6910 | 15.21 |
| 3 | 0.6414 | 13.42 |
| 4 | 0.5407 | 13.59 |
| 5 | 0.3860 | 14.32 |
| 6 | 0.0000 | . |

## 4. Results and Discussion

We first begin this section by showing results on whether women are interested in economic activities in general (RQ 1). We then discuss women's job aspirations in light of sustainability (RQ 2). Against the previously outlined background of the sustainability of beekeeping in terms of socio-economic and ecological benefits, we furthermore explore women's attitudes to beekeeping (RQ 3).

### *4.1. Income Generating Activities of Women*

The women in our sample are, on average, 37 years old and have 3.3 years of schooling. 44 percent are transmigrants, defined as individuals who moved—or whose families moved—to the study region typically as part of the government-sponsored transmigration program (Bazzi et al., 2016; Gatto et al., 2015). On average, the women live in a household of 4.4 members. Furthermore, 58 percent state to own assets (see Table 2).

**Table 2.** Cluster Description.

| | | Cluster (1) | | Cluster (2) | | Cluster (3) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Traders | | Education and health-oriented aspirations | | Other aspirations | | Total | |
| **Variable** | **Unit** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** | **mean** | **sd** |
| Age | years | 36.62 | 7.88 | 29.90 | 8.50 | 41.00 | 12.92 | 37.33 | 10.81 |
| Asset ownership | dummy[a] | .52 | - | .60 | - | .65 | - | .58 | - |
| Education | years | 3.00 | 1.10 | 4.50 | 1.27 | 3.12 | 1.11 | 3.28 | 1.23 |
| Household size | members[b] | 4.38 | 1.40 | 4.30 | 1.42 | 4.38 | 1.96 | 4.37 | 1.63 |
| Transmigrant | dummy[c] | 1.76 | - | 1.50 | - | 1.62 | - | 1.66 | - |

Note: [a] yes = 1, no = 0; [b] Number of members living under one roof; [c] yes = 1, no = 2.

As a first step, we answer a crucial question, which is posed through the work of Mehraban et al. (2022), namely whether women in palm oil households wish to participate in economic activities or if they are satisfied with the increased leisure time and generally higher household income generated through oil palm cultivation. We find that they wish to work and that they have a wide variety of aspirations. Notably, out of 65 women, only two stated an activity related to oil palm cultivation.

In Table A1, we report the women's stated activities, sorted by us into different categories, namely Administration, Farming, Sales, Services, Social, Nothing, and Undecided roles. The Administration category includes roles related to village governance and office work, while Farming encompasses various agricultural activities such as fish cultivation, livestock raising, and oil palm planting. The Sales category is rather detailed, listing various entrepreneurial activities, from running grocery stores and restaurants to selling specific goods like cakes and electronics. The Services category includes professions like tailoring and makeup, whereas the Social category highlights roles in education and community support, such as teaching and health services. Additionally, some individuals expressed uncertainty or a lack of desire to work. Out of 65 women, 7 fall into the Nothing category, with two stating that they do not want to work and the five others stating that there is no work available. Taken together, the table provides a comprehensive overview of occupational interests, reflecting a mix of entrepreneurial, agricultural, administrative, and social engagement within the community.

A first takeaway is that out of 65 women, 63 were generally willing and wanting to work. This is an interesting finding as palm oil cultivation yields a relatively good household income (compared to other possible crop portfolios of smallholder farmers in Indonesia). Thus, one could argue that women are hesitant to take up an economic activity and rather focus on their day-to-day chores. Our results indicate that this is not the case.

### *4.2. Cluster of Women Based on their Aspired Activities*

This section discusses the results of our cluster analysis, showing the relative distribution of the segmentation variables across the different clusters and the cluster characteristics by giving the mean values of socio-demographic characteristics. We begin by presenting attractive income generation activities stated by the women in our sample, organized as clusters that follow our cluster analysis.

Table 3 presents the clusters and illustrates the absolute frequency of the clustering variables in the three clusters. We determined the names of the individual clusters based on the most influential variables of the respective segment. Cluster 1 "Traders" (N = 29) consists of women who indicated that they wanted to work in anything trade-related, for example selling groceries or cakes. Cluster 2 "Education and health-oriented aspirations" (N = 10) is comprised of women who are interested in doing social work such as teaching or working in a hospital. Cluster 3 "Other aspirations" (N = 26) describes the women who indicated that they wanted to do administrative work in the farming or the service sector. This cluster also contains respondents who indicated that they wanted to work but were undecided. Out of 26 women, two women said that they did not want to work at all, and five women said they cannot work as there is no work available, which might still indicate a general work interest.

**Table 3.** Clustering Variables and Clusters.

| | Cluster (1) Traders | Cluster (2) Education and health-oriented aspirations | Cluster (3) Other aspirations | Total |
|---|---|---|---|---|
| **N** | **29** | **10** | **26** | **65** |
| Administration | 0% | 0% | 15% | 6% |
| Farming | 0% | 0% | 31% | 12% |
| Nothing | 0% | 0% | 27% | 11% |
| Sales | 100% | 0% | 0% | 45% |
| Services | 0% | 0% | 20% | 8% |
| Social | 0% | 100% | 0% | 15% |
| Undecided | 0% | 0% | 7% | 3% |

The Traders represent the biggest cluster, comprising 29 women. In this cluster, some women already participate in some trading activity. For example, one woman reported, "I've done it. I've been selling groceries and snacks since 2005." (see Table A1). One woman aspired to "enlarge the store," while another aimed to "increase selling capital." However, most women in this cluster aim to start a new business. Most commonly reported were activities related to food. This includes opening up a restaurant, starting a bakery, or selling groceries. Six women left the entrepreneurial domain undefined and just reported "selling," "own a shop," or "trade." Some women were envisioning other shops such as opening up a credit shop (1), opening up an electronic business (1), or opening up a boutique (1).

The Education and health-oriented aspirations build the smallest cluster with 10 women. All of these women stated that they want to be either a teacher (8) or a health service worker (2). Concerning teaching, one woman stated that she wanted to teach baking, one hoped to be an Al-Quran teacher, and another wished to open a community learning activity center. The other women just generally stated "teacher" or "lecturer." Concerning health services, one woman would like to open a health clinic, and the other one aspires to be a social rehabilitation assistant. While opportunities such as taking on a role in teaching or in healthcare can most definitely be income-generating activities, they also require certain levels of (formalized) training.

The Other aspirations comprise 26 women and a variety of business activities, as well as those who do not want to engage in any business activity. Four women were interested in an administrative job. One woman stated she would like to be a "village apparatus," one an "office employee," one very generally "administrative staff," and one wanting to advance "SMEs in the village." Eight women were interested in farming activities. Two of them stated to wanting to engage in the ongoing oil palm cultivation by "utilizing the entire palm tree" and invest in "more oil palm planting." Three of the women stated that they wanted to raise livestock—including rabbits, goats, and cattle—and/or fish. The others simply stated either general farming or that they wanted to have more gardens/more vegetables. Five women reported their wish to engage in the service sector. The most common activity stated was sewing (3). One woman wanted to open a make-up service, and one wanted to start a business of woven mats. Seven women stated that they do not want to work, either because they simply did not want to (2) or because they claimed there wasn't any work (5). Two women were undecided about what to say.

The Other aspirations group represents the richness and innovativeness of rural women. The varieties of ideas show great potential for further exploration of their potential as well as possible hurdles. The Traders tend to think of village-level entrepreneurial activities, which might be a reflection of preferences for starting a business close to the house. A restaurant or a bakery can be run from inside the house in rural regions, so the woman does not have to trade off between household/child care and her entrepreneurial activity. As women most probably possess the needed skills, e.g., to bake bread or cook food, as well as the needed equipment, it seems that women build the aspiration around low upfront-costs. This might appear to be a rational thought as rural regions tend to lack access to financial markets. However, many of the aspired economic activities of the "Traders" may have limited success opportunities due to the quick saturation of the rural (service) market.

The Other aspirations state a variety of business ideas. For example, keeping livestock complementary to oil palm cultivation is promising. Livestock can work as an asset for the household and/or nutrient-rich food contributing to the household's food security (Devendra, 2010; Moll, 2005). Especially small ruminants that reproduce quickly and have low feeding requirements (Gerbil et al., 2023). However, additional livestock and especially fish need additional space, a potential bottleneck. Administrative jobs, as also found in the Education and health-oriented aspirations, represent stable income activities but need to be publicly financed, which can be a critical limitation in rural regions where public funding structures are weak or informal.

Table 2 further describes the women in each cluster and presents the different sociodemographic results. The Traders are of medium age (36 years), have relatively low education (on average 3 years of formal education), relatively the lowest asset ownership (52% of households own assets), and are most likely to be transmigrants. Household size is rather similar between all three clusters, with 4.3–4.4 members living under one roof. The Education and health-oriented aspiration are the youngest (29.9 years of age, on average), and the most educated (on average, 4.5 years of formal education). The Other aspirations stand out for being, on average, the cluster with the oldest women (41 years) and the highest share of assets (65% of the households own assets).

Two interesting takeaways follow the insights shown in Table 2. First, there are considerable differences in sociodemographics between the groups. We find a variety of business aspirations within our sample and differences in age, education, asset ownership, and migration background between the clusters. Women in the villages represent a diverse group with diverse ideas and aspirations, a reminder that one size will not fit all. Second, we asked the women for job aspirations roughly within their current skill-set, which the women appear to have stuck to. The most educated women are in cluster 2, the Education and health-oriented aspirations cluster, i.e. those aiming to be teachers or health workers.

### *4.3. The Potential of Beekeeping for Rural Women's Economic Participation*

As previously argued, beekeeping presents itself as a promising activity for women in oil palm cultivating villages, with the potential to contribute to social, economic and ecological sustainability. Hence, we wanted to specifically elicit the perceptions of and attitudes towards beekeeping, beyond the clusters. Beekeeping holds immense potential in terms of socio-economic participation and ecological benefit. Of the women who participated in our study, 60% (39 women) expressed interest in beekeeping, whereas 40% (26 women) were opposed or hesitant to engage in this activity (see Figure 1). These responses indicate that a majority of participants were open to beekeeping. However, stated openness towards a hypothetical activity does not necessarily imply an intention to adopt. Nevertheless, the findings provide initial insights into women's perceptions of beekeeping as a potential economic activity.


**Figure 1.** Attitude towards Beekeeping (N = 65).

The reasons for being opposed or at least hesitant towards beekeeping activities are diverse[4]. We have categorized them into six groups in Table 4. First, lack of time/energy: The main reason women state for not wanting to engage. Women in this group report, for example, that "Because want to focus on business" or "exhausting" or "not strong enough to work." Second, Lack of information/think it is impossible: Seven women fall into this category. Statements include reservations "Never knew anyone who is a beekeeper" or "Never tried (no experience)," "Difficult," as well as logistical hurdles due to the distance from household to the botanic area "There is no interest because the fields/gardens are far away" or informational hurdles "Because the area is far from water [sources], and [my] mother said bees like to be near water." Third, Afraid of bees: Four women fall into this category and stated that they were generally afraid of bees (3) as well as being afraid of being stung (1). Fourth, Market Situation: Women are concerned about the unstable market situation, which includes the concern about price fluctuations in the market as well as the difficulty of marketing and maintaining the business. Fifth, General concerns of the Household: Two women gave reasons that fall into this category. One woman was concerned that her husband would not approve this enterprise, and the other felt beekeeping was out of place for her. Sixth, Lack of skills; one woman reported that she is unskilled and therefore she is not interested in beekeeping activities.

4 The following is based on 24 answers given by those who stated to be opposed/hesitant to take up beekeeping. Women stated their main reason for being opposed/hesitant to beekeeping, i.e. we recorded one reason per hesitant women.

**Table 4.** Reasons for Opposing Beekeeping by Category (N = 26).

| Assigned Category | Reasoning |
|---|---|
| Afraid of Bees | Afraid of bees |
| | Not painstaking |
| Afraid of Unstable Market | The market is uncertain |
| | Difficult marketing and maintenance |
| | Not interested yet |
| General Concerns in Household | Feeling out of place |
| | Husband does not allow |
| Lack of Information/ Think It Is Not Possible | Because the area is far from water |
| | Mother said bees like to be near water |
| | Difficult |
| | There is no interest because the fields/gardens are far away |
| | Never tried (no experience) |
| | Complicated. Farming paddy is enough |
| | Never know anyone who is a beekeeper |
| | Want to avoid complications |
| Lack of Skills | Being unskilled |
| Lack of Time/Energy | Confused about managing time |
| | Already old |
| | Want to focus on business |
| | Not strong enough to work |
| | Not interested, already has own work |
| | Bothered by taking care of it |
| | Exhausting |
| | Feels like a hassle |

Note: If a woman stated that she is not interested in beekeeping, we asked for a reason. All answers are reported in this table, one row per individual, sorted by category. Statements were translated from the original responses. Some responses were grouped into broader categories for clarity.

With all concerns being valid and similar to concerns identified in the literature (Wagner et al., 2019), many of these could be addressed. For example, *Lack of information/think it is impossible*, *Lack of skills*, *Market Situation*, as well as some of the concerns from other groups could be addressed through information and training sessions. Exploratory discussions with local beekeepers and the nongovernmental organization *Rumah Madu* (Indonesian for Honey House) in Jambi indicated that stingless bees can be kept close to the household with limited land requirements. However, successful adoption requires access to colonies, suitable forage, practical training, and marketing channels. Evidence from West Kalimantan similarly shows that successful colony establishment depends on hive location, colony transfer, and subsequent management (Ashari et al., 2019), while Gratzer et al. (2019) emphasize broader technical and ecological challenges for beekeeping in Indonesia. Further, *Fear of bees* could be addressed by taking up stingless bees instead of bees that sting—as both deliver honey—as well as by providing training and showing the bees to the farmers. However, how beekeeping is introduced and how the training is designed is critical to its success (Nat Schouten & John Lloyd, 2019; C. Schouten et al., 2019). Research shows that factors such as tradition and local conditions (Kumsa et al., 2021; C. N. Schouten, 2020), as well as tailored extension services, technology and market ties (Nat Schouten & John Lloyd, 2019; Thomas & Tounkara, 2020) and floral landscape (Nat Schouten & John Lloyd, 2019) are critical for beekeepers to be successful. That being said, beekeeping merely presents one possible option for additional complementary economic activity; it is not a general solution. While there is some limited empirical evidence from the region that communities can produce and sell honey (Ap et al., 2026), it is unknown how production, sale, and marketing would turn out particularly for women.

## 5. Conclusions

Despite the manifold positive outcomes of oil palm expansion, particularly in Indonesia, the adverse consequences are persistent and concerning: the loss of female participation in agricultural value creation and biodiversity losses are among the most concerning ones. This study contributes to solutions aiming to mitigate the adverse outcome of female work displacement by eliciting the diverse aspirations of rural women for economic participation and income opportunities. We identify possible pathways for female economic integration, while highlighting one particularly promising tool to foster the synergy between socio-economic and environmental benefits: Beekeeping. We thus investigated the attitudes of rural women towards beekeeping to understand whether there is a general interest. Using a sample of 65 women in rural oil palm cultivating villages in Jambi, we explore the different job aspirations women hold and which potentials they see for themselves to engage in economic activities.

We report three main results. Firstly, women aspire to a wide variety of economic activities, highlighting their general wish for economic participation. We answer a crucial question, which is posed through the work of Mehraban et al. (2021), namely whether women in palm oil households wish to participate in economic activities or if they are satisfied with the increased leisure time and generally higher household income generated through oil palm cultivation. We find that they wish to work. We further find that only two women want to work in an activity related to oil palm cultivation. Secondly, we could identify three clusters of women based on their aspired activities: "Traders," such as small (food) business owners; "Education and health-oriented aspirations," such as teachers or health care workers; and "Other aspirations," which encompasses a variety of activities such as engagement in post-harvest activities, handicraft, or administrative work. This mixed group represents the richness and innovativeness of rural women. The variety of ideas invites further exploration of their potential as well as the discussion of their hurdles. Hurdles mainly include critical risks of success due to lack of infrastructure or market saturation in rural regions. Thirdly, we investigate the role of beekeeping as an economic activity, which potentially caters to all three pillars of sustainability. Most of the women (60%) in our study were open to beekeeping. Those who were hesitant or opposed to beekeeping gave reasons that can mostly be addressed through information, training, or by keeping stingless bees in an extensive system.

This paper has taken an exploratory approach to examine whether, and in which economic activities, women in oil palm cultivating villages want to engage in. The findings are limited by our small convenience sample drawn from a case study in Jambi and by the self-reported nature of women's aspirations. The small number of observations within individual work categories also precludes reliable subgroup analyses of whether aspirations or interest in beekeeping varies by respondents' socioeconomic characteristics. Moreover, beekeeping serves as an example to assess women's openness to a hypothetical economic activity rather than its actual adoption or real-world feasibility. These limitations point to several avenues for future research. It will be an ongoing quest to drive sustainability and resilience within the oil palm sector, particularly in smallholding communities. Gender equality is a central goal of the SDGs, and closing the gender gap can have many positive spillovers to a number of other SDGs. Our study is a critical first step to further endeavors of policymakers and researchers in their quest to make the smallholder oil palm sector more resilient and sustainable. This study has shown that rural women in oil palm contexts have an interest in economic activities in general and are open to beekeeping. We thereby set the stage for stakeholders to foster economic participation among rural women.

The aspirations expressed by the women in our study extended beyond conventional agricultural activities and included food processing and sales, trade, and other forms of self-employment. This diversity highlights the importance of avoiding a one-size-fits-all approach to women's economic empowerment. Hence, interventions should begin by identifying women's own priorities and assessing how different activities fit their skills, interests, and household responsibilities, as well as local market conditions. Future research should therefore examine the feasibility of different aspirations identified in this study, the constraints preventing women from pursuing them, and the types of training, finance, infrastructure, or institutional support required to translate aspirations into viable livelihood opportunities.

Beekeeping may represent one such opportunity for women who express an interest in the activity, but it should not be presented as a general solution for women in oil palm cultivating villages. However, its suitability and potential contribution to women's empowerment depend on women's decision-making power concerning production and income, as well as on labor requirements, access to knowledge and productive resources, household support, and viable markets for honey and related products. Future interdisciplinary research should assess these conditions alongside the economic viability and potential ecological benefits of beekeeping. Important avenues for future research are testing the potential of beekeeping among rural women, potentially in the form of randomized controlled trials. While our findings indicate that a majority of participants were open to beekeeping, future research is needed to assess actual adoption, income effects, market demand and potential sustainability benefits. Researchers should critically test if beekeeping delivers the anticipated benefits and can develop as a genuinely bottom-up activity initiated and driven by women within their communities, rather than as an externally imposed intervention.

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## Appendix A

**Table A1.** Aspired Economic Activities by Category: Translated Statements.

| Assigned Category | Jobs Including Skills |
|---|---|
| Administration | Administrative staff |
| | Advancing SMEs in the village |
| | Village apparatus |
| | Office employee |
| Farming | Farming |
| | Fish cultivation |
| | Have more gardens |
| | More oil palm planting |
| | Raise cattle |
| | Raising fish, rabbits, goats |
| | Utilizing the entire palm tree |
| | Vegetable farming |
| Nothing | Don’t want it |
| | Don’t want to work |
| | There isn’t any |
| | There isn’t any |
| | There isn’t any |
| | There isn’t any |
| | There isn’t any |

**Table A1.** *Cont.*

| Assigned Category | Jobs Including Skills |
|---|---|
| Sales | I've done it, I've been selling groceries and snacks since 2005 |
| | Selling business |
| | Owns a restaurant |
| | Have an electronics business |
| | Enlarge sales business |
| | Own a shop |
| | Open a grocery shop |
| | Have a culinary business |
| | Open a boutique |
| | Open a grocery trading business |
| | Open a bakery business |
| | Selling |
| | Enlarge the store |
| | Selling cakes |
| | Selling groceries |
| | Trade |
| | Food business |
| | Open a business (grocery store) |
| | Open a food stall |
| | Open a grocery store |
| | Food business |
| | Open a vegetable shop |
| | Own a restaurant business |
| | Increase selling capital |
| | Own shop |
| | Opening a food business |
| | Selling (open credit shop) |
| | Have a bigger warung |
| | Selling |
| Services | Makeup |
| | Business of woven mats from tassel (pandanus plant species) |
| | Tailoring |
| | Opened a sewing business |
| | Take a sewing course |
| Social roles | Al-Quran teacher |
| | Become a teacher |
| | Lecturer |
| | Opened a community learning activity center |
| | Open a health clinic |
| | Social rehabilitation assistant |
| | Teach baking |
| | Teacher |
| | Teacher |
| | Teacher |
| Undecided | Don't know |
| | Yes |

Note: All answers are reported in this table, one row per individual, sorted by category. Statements were translated from the original responses. Some responses were grouped into broader categories for clarity.

**Appendix B**

**Complete Questionnaire**

1. How old are you?
– ____ years
2. How many people live in your household, including yourself?
– ____ people
3. What's your highest school degree?
– No school
– Elementary School
– Middle School
– High School
– Bachelor
– Master
– Other, please specify: ___________
4. Did you or your parents/your husband or his parents participate in the transmigration-program?
– Yes
– No
5. Are you currently working?
– Yes, on-farm
– Yes, off-farm
  If yes, please specify your type of work: ___________
– No
  If No, would you like to work?
• Yes, on-farm
• Yes, off-farm
• No
6. If you are currently working, are you being paid for your work?
– Yes
– No
7. If you are currently working, how difficult or easy was it for you to get this job (scale from 0 to 5)?
– ____ (0 = very difficult, 5 = very easy)
8. If you are currently not working, did you ever work before?
– Yes
– No
9. If you are currently not working, would you want to work?
– Yes
– No
– What type of job did you last have? ___________
– Did you like this job?
• Yes
• No

- Why did this last job end? ___________
- How long did you work last? ___________
- When did you stop working (year)? _____

10. Would you say palm oil cultivation has made it difficult for women to work compared to the time before palm oil was cultivated?
- Yes
- No
- If yes, why? ___________

11. Would you want to cultivate oil palm?
- Yes
- Yes, but with a caretaker
- No
- If no, why not? ___________

12. How long has your family/household been cultivating oil palm? (since year _____)
13. Would you say that due to oil palm cultivation it is no longer necessary for women to work because e.g. the husband generates enough income?
- Yes
- Yes, but I would still like to generate my own income
- No

14. Did oil palm cultivation change your household income?
- ___________

15. If yes, how did oil palm cultivation change your household income? Do you have more money now or less?
- ___________

16. Do you have more leisure time?
- ___________

17. If yes, do you enjoy having more leisure time?
- ___________

18. Do you know any women cultivating/owning oil palm plantations?
- Yes
- No

19. What are possible jobs/what is a typical work for women in villages or areas where lots of oil palm is cultivated?
- ___________

20. With your skillset and your talents, which job would you like to do if you had the money/training to realize it?
- ___________

21. Regardless of your skillset and talents and education, what would you like to work?
- ___________

22. Would you be open to an income source which you could pursue from your home (e.g. handicraft, food crops, …)?
- Yes

- No
- I don't know

23. How many hours per day are you currently working and how many hours per day would you like to work?

- Currently working: ____ hours
- Would like to work: ____ hours

24. Do you have ideas for viable businesses in your area?

- ___________

25. Would you be open to work with bees and honeymaking?

- Yes
- No
- Could you explain why (not)? ___________

26. Do you own any assets (money, house, land, motorbike, …)?

- Yes
- • Please specify: ___________
- No

27. Do you own a bank account?

- Yes
- No
- No but I have full access to a bank account

28. Are you married?

- Yes
- No

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Agricultural & Rural Studies

*Article*

# Determinants of CSA Adoption in Coastal Bangladesh: An Application of Structural Path Analysis

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**Abstract:** Climate-smart agriculture (CSA) is widely promoted to reconcile productivity, resilience, and emissions goals among smallholder farmers, yet adoption of capital-intensive CSA technologies remains low and uneven in climate-vulnerable coastal agriculture. This study examines socio-demographic, institutional, and behavioral determinants of CSA adoption among farming households in selected coastal districts of Bangladesh. This cross-sectional study interviewed 386 farmers from 3 selected coastal districts of Bangladesh following a multi-stage random sampling. Results were interpreted using descriptive statistics, Spearman's correlation, adoption-difficulty (quadrant) analysis, and structural path analysis. Adoption levels varied widely across 30 CSA practices. Low-cost, knowledge-based practices such as raised bed homestead gardening, airtight seed storage, and heat and salinity-tolerant crops were widely adopted, whereas capital-intensive technologies such as poly-net houses, solar irrigation, and the *sorjan* method remained rare. Extension communication showed the strongest association with extension strategies for promoting CSA ($\beta = 0.551$), whereas strategies for promoting CSA, knowledge of CSA, and climate change perception were important predictors of CSA adoption. Importantly, the ICT usage had a negative relationship with climate change perception, indicating a digital paradox whereby the higher connectivity does not lead to a better understanding of the issues related to climate change. The research shows that there is a necessity for combined extension approaches based on face-to-face extension efforts, participatory learning platforms, and credible digital technologies combined with strong farmer organizations for increasing CSA adoption in coastal Bangladesh.

**Keywords:** climate-smart agriculture; structural equation modeling; path analysis; agricultural extension; coastal Bangladesh

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## 1. Introduction

Climate change is the most critical threats to global food security, and its effects are overwhelmingly felt in agrarian economies where agriculture remains extremely vulnerable to weather changes (Hasan et al., 2018; Lipper et al., 2014). The warming trend, change in rainfall patterns, and the occurrence of extreme weather phenomena are factors that have started changing how crops perform and decisions made at the farm level (Agyekum et al., 2024). Among such environments that remain under threat from the adverse impact of climate change are lowlands that are affected by the following environmental conditions – salinity intrusion, tropical cyclones, tidal flooding, and waterlogging (Ahmad, 2019; M. A. Rahman et al., 2025).

Bangladesh is well known as one of the most vulnerable countries in terms of climate change. The southern coastal region of Bangladesh presents an example of vulnerability in its extreme form. Areas such as Patuakhali and Bhola have been found to be affected by the presence of many rivers and estuaries, which makes them vulnerable to cyclones, storm surges, and increasing levels of soil and water salinity (Antu et al., 2025; Hoque et al., 2023; M. S. Rahman et al., 2023). Due to such environmental stresses, the productivity of traditional crop-growing practices is decreasing day by day, and farming families have had to change their practices in terms of what they grow (Akter et al., 2022; Begum, 2023). In such a scenario, CSA can be regarded as a method to increase agricultural productivity, build resilience against the impacts of climate change, and reduce GHG emissions (FAO, 2013; Mia & Roy, 2025; Zhao et al., 2023).

Although there is increased policy interest in CSA, the implementation of CSA by smallholder farmers has proved to be uneven and disappointing in many places. Ageing of the farming population, lack of formal education, and lack of participation in new technological developments have made it difficult for farmers to adopt new technologies that promote climate-smart agricultural development (Anuga et al., 2019; Atta-Aidoo et al., 2022). Formal education has been identified as an effective tool for enhancing agricultural technology adoption because it increases cognitive ability and the processing and use of climate information (Oli et al., 2025). Constraints in the structures of small-scale farming make it even harder for small-scale farmers to benefit from climate-smart agricultural development (Barasa et al., 2021; Naveen et al., 2024).

A closely linked set of evidence shows that there is a clear pattern of a similar adoption gradient in favor of low-cost, knowledge-based CSA methods versus capital-intensive, infrastructure-reliant technological innovations (Howlader et al., 2026a). It appears that farmers prefer gradual, relatively safe changes in the form of crop diversification, cultivation of stress-resistant crops, and grain and seed storage rather than radical innovations as a manifestation of rational risk-minimization under climate uncertainty (Zheng et al., 2024). This takes place when financial limitations and risks influence the choice of adaptation (Anugwa et al., 2022; Billah et al., 2025; J. R. Sarker et al., 2026). Consistently low rates of technology adoption, including such ones as Alternate Wetting and Drying (AWD) irrigation and solar irrigation systems, indicate that diffusion obstacles go far beyond mere lack of awareness to include limited access to credit and poor infrastructure and input/output market connections, which in turn depend on liquidity (Billah et al., 2025; Ruba et al., 2024; Ulucak et al., 2026).

The ability to access knowledge and information, through interpersonal extension, organization participation, or information and communication technology (ICT), has been found time and again to be an essential ingredient for adaptation. This is in line with the knowledge-attitude-practice model, where the acquisition of information serves as a necessary step towards behavioral change (Kifle et al., 2022), and also diffusion-of-innovation theory, where the importance of adopters and communication channels in the adoption of technological innovation in rural communities is emphasized (Colton, 2015; Rogers, 2003). Multi-channel communications have been found to promote adaptation and reduce information asymmetry within the farming community (Oyelami et al., 2022; Wang et al., 2026). However, traditional and interpersonal extension methods still prove to be more effective than digital means in settings where there is low digital literacy and ICT infrastructure (Aslam, 2025; Fabregas et al., 2019), and institutionalized participatory extension methods like Farmer Field Schools, despite research showing their effectiveness in promoting the adoption of sustainable agriculture (Ongachi et al., 2026; Waddington et al., 2012), still remain underutilized. However, the positive impacts of ICT in relation to agricultural adaptation have become questionable as more evidence becomes available that there exists what can be referred to as a "digital paradox," where increased digital connection may not necessarily lead to enhanced climate awareness and adaptive practices, potentially reflecting factors such as misinformation, poor-quality content, or limited local relevance (Gumbi et al., 2023). The question then is how digital engagement is complementing or replacing extension in the adaptation process of farmers in coastal areas, something which is yet to be fully understood in Bangladesh.

The role of organizational participation in enhancing social capital, collective learning, and access to extension services is also well-documented, highlighting the significance of farmer organizations and institutional collective action in influencing adoption outcomes, especially in agroecological systems exposed to risks (Husen et al., 2017; Ma et al., 2023). At a broader level, these dependencies between individual characteristics, institutions, and information flow reflect the concept of Agricultural Innovation Systems (AIS), where adoption of innovations is not seen as an end in itself, but rather the outcome of interactive processes involving actors, institutions, and technologies (Gutiérrez et al., 2023; M. S. Rahman et al., 2023).

Most of the existing research on CSA adoption, on the contrary, considers those determinants separately, employing correlation or regression analysis techniques that perceive knowledge, extension communication, ICT use, organization involvement, and climate perception as equivalent predictors without seeing their connection as a chain of pathways. Such an approach may not be considered the most appropriate one, as it is unlikely that farmer decisions about adopting new technologies are affected by only one factor that operates alone; rather, adoption can be considered a consequence of several sequential processes: extension communication resulting in knowledge acquisition, knowledge formation leading to strategic behavior, and strategic behavior causing adoption. Moreover, the coastal south-central part of Bangladesh, characterized by its adaptation challenges due to high salinity levels, cyclones, and waterlogging, is rather understudied compared to other ecological zones in the country.

In this context, the current study tries to bridge three gaps in knowledge which are interlinked with each other. First of all, it transcends the traditional approach based on univariate or correlational analysis by using structural equation modeling (path analysis) to examine the hypothesized structural pathways among innovativeness, organizational participation, extension communication, ICT use, knowledge, climate perception, extension exposure, and CSA practice adoption of coastal farmers. Second, it studies the effects of ICT usage on climate change perception, providing empirical insight into the current controversy about whether ICT-based agricultural information systems increase or decrease farmers' awareness of climate change. Finally, it draws attention to two very important and yet underexplored climate-exposed areas of coastal Bangladesh, namely Patuakhali and Bhola districts.

Thus, this study intends to (i) measure the magnitude and structure of adoption of CSA practices by coastal farmers, (ii) analyze the level of exposure of farmers to different agricultural extension approaches, and (iii) develop a structural relationship between different factors influencing farmers and their adoption of CSA practices. The goal of this study is to develop practical and evidence-based recommendations that will help develop effective hybrid strategies for agricultural extension, which will combine the conventional approach with the validated digital platform.

*Conceptual Framework*

The conceptual framework guiding this study is grounded in the principle that CSA adoption is not a direct behavioral outcome of individual or institutional attributes, but rather an outcome mediated by farmers' knowledge, strategic engagement, and perceptual orientation toward climate change. As illustrated in Figure 1, the framework organizes the study variables into three conceptual tiers. The first tier comprises antecedent factors such as innovativeness, extension communication, use of ICT, and organizational participation, which represent farmers' individual traits and their embeddedness within information and institutional networks. These antecedent factors are theoretically and empirically interrelated, as farmers with greater organizational participation tend to have broader ICT exposure and extension communication, consistent with the correlational structure reported in Table 8. The second tier consists of three mediating mechanisms: knowledge on CSA, extension strategies for promoting CSA, and climate change perception. Through these mediating mechanisms, the antecedent factors are hypothesized to exert their influence.

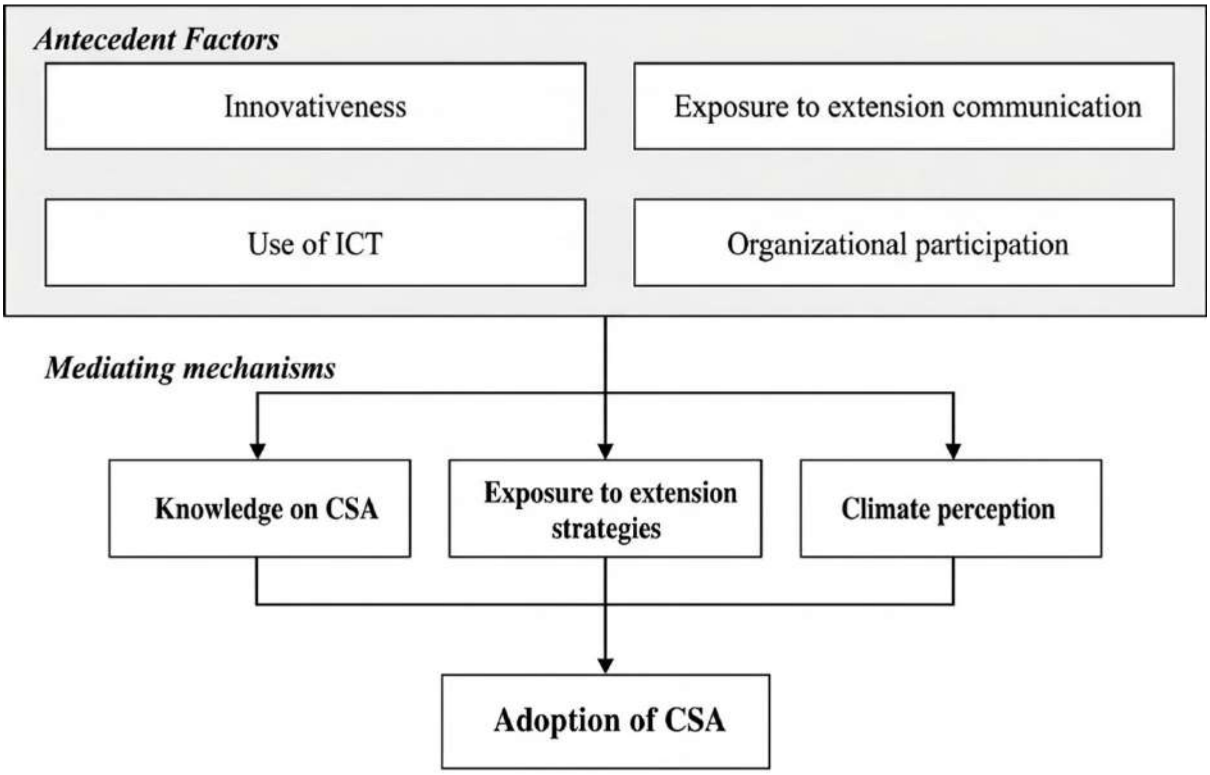


**Figure 1.** Conceptual framework of the study.

The mediating construct takes inspiration from the knowledge-attitude-practice (KAP) model, which proposes that acquisition of knowledge is prior to attitudinal and behavioral change (Kifle et al., 2022), and the diffusion-of-innovation theory, which states that communication media and personal innovativeness play important roles in the process of adoption of innovations (Rogers, 2003). The third level stands for the final behavioral goal of interest for CSA practices adoption, which is supposed to be driven by the three mediators, not by the antecedent variables directly, since the conceptual framework proposes that these mechanisms may transmit part of the association between antecedent factors and CSA adoption and therefore is in line with the AIS approach to innovation. Where adoption happens because of the interaction of actors, information, and institutions, but not simply individual attributes. In the proposed framework, the most influential antecedent is extension communication due to its importance for improving farmers' knowledge and their strategic involvement in the practice of CSA; meanwhile, the use of ICT has an independent function of positively affecting strategic involvement in this framework.

## 2. Methodology

### *2.1. Study Design and Settings*

This study employed a cross-sectional study design to examine farmers' adoption behavior, knowledge, perception, and institutional exposure regarding CSA practices adoption in south-central coastal Bangladesh. The study was conducted in three coastal districts, Patuakhali, Barguna, and Bhola, which are highly vulnerable to climate change impacts such as salinity intrusion, cyclones, waterlogging, and erratic rainfall. These environmental stresses significantly influence agricultural productivity and farmers' adaptation decisions by using CSA practices.

### *2.2. Population and Sampling Procedure*

The study population comprised all farmers residing in the three selected districts. A multistage random sampling technique was applied to select respondents. In the first stage, one upazila such as Kalapara, Taltali, and Charfesson from Patuakhali, Barguna, and Bhola District was randomly selected respectively (Figure A2). In the second stage, one agricultural block was selected from each upazila. Thus, three agricultural blocks constituted the primary sampling units. A complete sampling frame was developed using farmer lists obtained from the respective Sub-Assistant Agriculture Officers (SAAO) of each selected block. These lists served as the official population frame for respondent selection. After completing the frame, respondents were selected randomly. The sample size was determined using the Krejcie & Morgan (1970) formula at a 95% confidence level, 5% margin of error, and 50% population proportion. Finally, this study included a total of 386 samples in the analysis.

### *2.3. Data Collection*

Data were collected through face-to-face interviews to ensure accuracy and completeness. Verbal informed consent was obtained from the respondents. At first, a pilot test was conducted among 30 participants with the interview schedule covering three study locations to obtain valid and reliable data. For the multi-item composite variables, reliability and internal consistency were tested using Cronbach's alpha (α) statistics following Howlader et al. (2026b), which are shown in Table 1.

**Table 1.** Reliability and consistency indicators for composite items of variables.

| Sl. | Name of variables | Number of items | Cronbach's alpha (α) |
|---|---|---|---|
| 1 | Extension communication | 10 | 0.700 |
| 2 | Knowledge of CSA | 12 | 0.869 |
| 3 | Innovativeness | 08 | 0.739 |
| 4 | Perception of climate change | 15 | 0.670 |
| 5 | Extension strategies for promoting CSA | 24 | 0.885 |
| 6 | Adoption of CSA practices | 30 | 0.700 |

The scale demonstrated good internal consistency posing values around the accepted level of α-threshold (0.70; Nunnally & Bernstein, 1994), while the climate-change perception scale showed a bit lower internal consistency (α = 0.670).

Based on the responses and compatibility, necessary refinements were made before final data collection. The final questionnaire included sub-sections on socio-economic characteristics, farm attributes, extension communication, organizational participation, innovativeness, ICT usage, knowledge on CSA, perception of climate change, CSA adoption behavior, and participation in extension strategies. The instrument included multiple measurement formats such as dichotomous (Yes/No), categorical, and ordinal rating scales. CSA adoption and extension exposure were measured using Likert scales, while knowledge was assessed using a structured scoring system (correct = 2, partially correct = 1, incorrect = 0).

### *2.4. Measurement of Variables*

#### 2.4.1. Socio-Economic Characteristics

Socio-economic variables were measured using a combination of direct numerical reporting and categorical classification to ensure precision and analytical suitability. Age and farming experience were recorded in full years; education was measured as years of schooling; farm size was measured in hectares by aggregating owned, leased, sharecropped (*Borga*), and cultivated land holdings (U. K. Sarker et al., 2022). Annual household income was measured in Bangladeshi Taka (BDT) and derived from both agricultural sources (crop production, livestock, poultry, fisheries) and non-agricultural sources (business, services, and wage labor).

#### 2.4.2. Extension Communication

Extension communication was measured using a 5-point Likert scale (0 = not even once, 1 = once, 2 = twice, 3 = three times, 4 = four or more times within the reference period) consisting of 10 items. Items included communication with Sub-Assistant Agriculture Officers (SAAO), Upazila Agriculture Officers, input dealers, model farmers, development workers, group discussions, field demonstrations, field days, agricultural fairs, and mass media platforms such as television, radio, newspapers, mobile applications, and social media. Sum of all 10 items reporting as extension communication. A higher score indicates better communication among coastal Famers. In this study, the obtained score of extension communication ranges from 1–34.

#### 2.4.3. Organizational Participation

Organizational participation was measured by 6 items consisting of questions. This included farmers' involvement in local institutions such as farmer groups, cooperatives, NGO-led groups, village committees, and market-related committees. Participation was categorized into levels including no participation, general membership, executive membership, and meeting attendance (regular, sometimes, or not at all).

#### 2.4.4. Innovativeness

Innovativeness was assessed by measuring the time lag between farmers' awareness and adoption of agricultural innovations. Respondents were categorized into non-adopters, adopters within 1 year, 2 years, 3 years, 4 years, and more than 4 years after exposure. Lower time lag indicated higher innovativeness. The total score ranged from 6–40.

#### 2.4.5. ICT Utilization in Agriculture

ICT utilization was measured using a 6-item scale consisting of the use of digital and communication tools for agricultural information. These included mobile phone calls, mobile applications, call centers, Facebook, YouTube, and WhatsApp. Each item was rated on a four-point frequency scale: regularly (more than three times per month), sometimes (2–3 times per month), seldom (once per month), and not at all. A composite ICT usage index was computed by summing all item scores. The total score ranged from 0 to 20 in this study.

#### 2.4.6. Knowledge of CSA

Knowledge was measured using an objective structured questionnaire covering key CSA concepts such as climate-resilient crop varieties, water-saving irrigation techniques, soil conservation, pest management, and adaptation strategies. Each response was scored as 2 for correct, 1 for partially correct, and 0 for incorrect answers. The total knowledge score was obtained by summing all item scores, where higher scores indicated greater CSA knowledge. In this study, the knowledge score ranged from 3–28.

#### 2.4.7. Perception of Climate Change

Perception of climate change was measured using a 4-point Likert scale. This scale consists of 15 items, including temperature, rainfall pattern, salinity intrusion, cyclone frequency, pest and disease incidence, crop yield variability, biodiversity, and irrigation water availability. Responses were recorded as 3 = increased, 2 = decreased, 1 = no change, and 0 = don't know, and the sum of the total score was included as the perception of climate change. The total score ranged between 21–45 in this study.

#### 2.4.8. Extension Strategies for Promoting CSA

Extension strategies for promoting CSA were measured using a 24-item questionnaire with a four-point Likert scale. Responses were recorded as 3 = regular, 2 = sometimes, 1 = seldom, and 0 = not at all. Extension strategies for promoting CSA scores ranged from 3 to 56 in this study. Extension strategies for promoting CSA were ranked based on the weighted mean score. The formula used to calculate the Weighted Mean for 386(N) is:

$$\text{Weighted Mean} = \frac{(\text{Never} \times 0) + (\text{Rarely} \times 1) + (\text{Sometimes} \times 2) + (\text{Always} \times 3)}{386} \quad (1)$$

2.4.9. CSA Practices Adoption

Adoption of CSA practices was measured using a 30-item scale with a four-point Likert scale. Responses were recorded as 3 = regular, 2 = sometimes, 1 = seldom, and 0 = not at all, following Bhuiya et al. (2024). A higher CSA adoption practices score indicates better adoption among coastal farmers, with a total score ranging from 23–77. The adoption index was calculated using the weighted mean score. The weighted mean for each CSA practice adoption was calculated using the following formula:

$$\text{WM} = \frac{\left(\sum_{i=1}^{n}(f_i \times w_i)\right)}{N} \tag{2}$$

Where,
WM = Weighted Mean
$f_i$ = Frequency of the "$i$" th response
$w_i$ = Weight of the "$i$" th response (3, 2, 1, 0)
$N$ = Total number of respondents (386)
$n$ = Number of categories

Moreover, an effort was made to compare the relative adoption of different practices and calculate the CSA practice "adoption index" score for each of the 386 respondents (Bhuiya et al., 2024; Moonmoon, 2021). To achieve this goal, an adoption index (AI) was employed with the formula stated below (Mia & Roy, 2025).

$$\text{AI} = \frac{\text{WM}}{\text{MS}} \times 100 \tag{3}$$

Where,
AI = CSA Adoption Index
WM = Weighted mean calculated by formula 1
MS = Maximum possible score (for this study it would be 3)

2.4.10. Measurement of Adoption Difficulty

The perceived implementation difficulty of each CSA practice was measured using a five-point Likert scale ranging from 1 (very easy) to 5 (very difficult). The difficulty score (DS) for each practice was calculated as the weighted mean of farmers' responses:

$$\text{Difficulty score (DS)} = \frac{\left(\sum_{i=1}^{n}(f_i \times d_i)\right)}{N} \tag{4}$$

Where,
DS = Difficulty Score of a CSA practice
$f_i$ = Frequency of respondents selecting the $i$th difficulty category
$d_i$ = Assigned score of the $i$th difficulty category (1 = Very easy, 2 = Easy, 3 = Moderate, 4 = Difficult, 5 = Very difficult)
$N$ = Total number of respondents

2.4.11. Adoption Difficulty Matrix Analysis

The adoption–difficulty matrix is theoretically equivalent to the Importance-Performance Analysis (IPA), where two aspects of performance are considered together in order to facilitate decision-making. In the current study, adoption and the perceived implementation difficulty were adopted as the two aspects in order to categorize CSA practices based on their extension and policy priority. To assess both the adoption and perceived implementation difficulty of CSA practices at the same time, an adoption-difficulty matrix was constructed using the adoption index against difficulty scores for each practice.

### *2.5. Data Analysis*

All descriptive statistics (frequency, percentage, mean, and standard deviation) were determined using SPSS 27.0.1. Path analysis was conducted using IBM SPSS AMOS (version 24) to examine the hypothesized structural relationships among innovativeness, organizational participation, extension communication, use of ICT, knowledge on CSA, extension strategies for promoting CSA, perception of climate change, and CSA practice adoption. The model fit was evaluated using standard goodness-of-fit indices, including Chi-square statistics, Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), and NFI = Normed Fit Index; RMSEA = Root Mean Square Error of Approximation. A significance value was set (p = <0.05). Mendeley was used to manage the citations and references.

## 3. Results

### *3.1. Socio-Demographic Characteristics of Respondents*

The socio-demographic profile of the respondents is presented in Table 2. The results indicate that nearly half of the respondents were middle-aged (36–50 years; n = 180, 46.8%), followed by older farmers aged 51–66 years (n = 103, 26.6%), and young farmers (18–34 years). Educational attainment was relatively low to moderate: 17.8% (n = 69) had no formal education, 37% (n = 143) had primary education, and about 45% (n = 175) had secondary education or above. Regarding farm size, 52.30% (n = 202) were smallholders (≤ 247 decimals), 34.70% (n = 134) were medium-scale farmers, and 13% (n = 50) operated large farms. More than half of the respondents (n = 207, 53.6%) reported no training exposure, while only 11.2% (n = 43) had long-duration training (≥ 6 days). In terms of farm location, 53.9% (n = 208) resided at a moderate distance (6–8 km) from the Upazila center, followed by 27.6% living nearby (≤ 5 km) and 18.6% in distant areas (≥ 9 km). Farming experience was relatively high, as 54.1% (n = 209) had up to 20 years of experience, while 45.9% (n = 177) had more than 20 years. Income distribution showed that 51.5% (n = 199) belonged to the low-income group, 37.5% (n = 145) to the medium-income group, and only 11.1% (n = 42) to the high-income group.

**Table 2.** Socio-demographic Characteristics of the participants.

| Variables | Frequency (n) | Percent (%) |
|---|---|---|
| Age (years) | | |
| Young (18–35) | 103 | 26.70 |
| Middle-aged (36–50) | 180 | 46.60 |
| Older (≥ 51) | 103 | 26.70 |
| Education | | |
| No formal education | 69 | 17.87 |
| Primary education | 143 | 37.05 |
| Secondary education | 111 | 28.76 |
| Higher secondary and above | 63 | 16.32 |
| Farm size | | |
| Small (≤ 247 decimals) | 202 | 52.33 |
| Medium (248–499 decimals) | 134 | 34.72 |
| Large (≥ 500 decimals) | 50 | 12.95 |
| Training experience (days) | | |
| No training (0 days) | 207 | 53.63 |
| Short training (1–5 days) | 136 | 35.23 |
| Long training (≥ 6 days) | 43 | 11.14 |
| Farm distance from Upazila (km) | | |
| Near (≤ 5 km) | 107 | 27.72 |
| Moderate (6–8 km) | 208 | 53.88 |
| Far (≥ 9 km) | 71 | 18.40 |
| Farming experience (years) | | |
| ≤ 20 years | 209 | 54.15 |
| > 20 years | 177 | 45.85 |
| Annual income | | |
| Low (≤ 2.0) | 199 | 51.55 |
| Medium (2.1–4.0) | 145 | 37.57 |
| High (> 4.0) | 42 | 10.88 |

**Table 2.** *Cont.*

| Variables | Frequency (n) | Percent (%) |
|---|---|---|
| Extension communication | | |
| Low (≤ 11) | 205 | 53.11 |
| Medium (12–22) | 163 | 42.23 |
| High (≥ 23) | 18 | 4.66 |
| Organizational participation | | |
| Yes | 214 | 55.44 |
| No | 172 | 44.56 |
| Perception | | |
| Low (≤ 29) | 38 | 9.84 |
| Medium (30–37) | 194 | 50.26 |
| High (≥ 38) | 154 | 39.90 |
| Knowledge on CSA | | |
| Low (≤ 12) | 137 | 35.49 |
| Medium (13–20) | 227 | 58.81 |
| High (≥ 21) | 22 | 5.70 |
| Use of ICT | | |
| No (0) | 39 | 10.10 |
| Low (≤ 6) | 221 | 57.26 |
| Medium (7–13) | 107 | 27.72 |
| High (≥ 14) | 19 | 4.92 |
| Innovativeness | | |
| Low (≤ 17) | 45 | 11.65 |
| Medium (18–29) | 144 | 37.31 |
| High (≥ 30) | 197 | 51.04 |

### *3.2. Adoption of CSA Practices*

The adoption pattern of CSA practices is summarized in Table 3. Overall, adoption levels varied substantially across practices. High adoption was observed among several low-cost, knowledge-based practices.

**Table 3.** Distribution of CSA adoption among farmers (N = 386).

| Rank | CSA Practice | Weighted mean | Adoption index | Perceived Difficulty score |
|---|---|---|---|---|
| 1 | Raised bed homestead gardening | 2.487 | 82.90 | 2.67 |
| 2 | Less water-required crop cultivation | 2.466 | 82.22 | 2.08 |
| 3 | Calibrating planting time with weather | 2.464 | 82.13 | 1.42 |
| 4 | Heat-tolerant crop | 2.322 | 77.41 | 2.33 |
| 5 | Salinity-tolerant crop | 2.307 | 76.89 | 1.92 |
| 6 | Short-duration crop | 2.286 | 76.2 | 1.83 |
| 7 | Airtight pot for seed storage | 2.278 | 75.95 | 3.25 |
| 8 | Weather forecast-based farming | 2.17 | 72.34 | 3.58 |
| 9 | Waterlogging-resistant rice | 2.015 | 67.18 | 1.67 |
| 10 | Foliar spray of micro-nutrient | 1.987 | 66.24 | 2.25 |
| 11 | Crop diversity | 1.827 | 60.91 | 2.08 |
| 12 | Rainwater harvesting/mini pond water reservoir | 1.802 | 60.05 | 3.41 |
| 13 | Extra seed storage for disaster risk | 1.796 | 59.88 | 2.00 |
| 14 | Integrated farming (crops-fish-poultry-cattle) | 1.794 | 59.79 | 4.00 |
| 15 | Vermicompost /compost use | 1.657 | 55.24 | 3.00 |
| 16 | Using eco-friendly pheromone and sticky traps | 1.608 | 53.61 | 3.08 |
| 17 | Ridge–furrow bed preparation | 1.593 | 53.09 | 3.33 |
| 18 | Aroid cultivation in lowland | 1.559 | 51.98 | 1.75 |
| 19 | Using ash | 1.503 | 50.09 | 1.83 |
| 20 | Biopesticide | 1.43 | 47.68 | 2.92 |
| 21 | Solar irrigation | 1.418 | 47.25 | 3.83 |
| 22 | Mulching | 1.299 | 43.3 | 1.50 |
| 23 | Drought-tolerant crop | 1.222 | 40.72 | 2.42 |
| 24 | Sorjan method of cultivation | 1.216 | 40.55 | 3.50 |
| 25 | Incorporating crop residue in the field | 1.216 | 40.55 | 3.17 |
| 26 | Sack method of cultivation | 1.101 | 36.68 | 2.17 |
| 27 | Alternate Wetting and Drying (AWD) | 0.99 | 32.99 | 2.75 |
| 28 | Poly-net house | 0.845 | 28.18 | 2.83 |
| 29 | Bottle drip irrigation | 0.835 | 27.84 | 2.83 |
| 30 | Multi-layer agriculture with Agroforestry | 0.631 | 21.05 | 3.50 |

Table 3 presents details of the adoption index and the perceived implementation difficulty of 30 CSA practices. The adoption index of the different practices was observed to vary between 21.05 and 82.90. This demonstrates the variations in terms of the level of adoption of CSA practices among the farmers of the coastal regions. On the other hand, the difficulty scores of implementations were recorded to be in the range of 1.42 to 4.00 out of 5. Higher scores indicate difficulty in implementing practices. Among the different CSA practices, the highest adoption index was found for raised-bed homestead gardening at 82.90%. Less water-consuming crop farming had an adoption index of 82.22%, while calibration of planting time with the weather had an index of 82.13%. All of these three practices had relatively low-to-moderate difficulty scores in implementing (2.67, 2.08, 1.42 respectively). This result suggests that farmers readily adopt practices that are comparatively easy to implement and provide visible benefits.

On the other hand, multi-layered farming along with agroforestry had the lowest adoption index (21.05%) with a high difficulty rating (DS = 3.50). The practices having low adoption rates along with relatively high difficulty perception include poly-net sheds (28.18%, DS = 2.83), bottle drip irrigation (27.84%, DS = 2.83), and *Sorjan* cultivation (40.55%, DS = 3.50). This may be because of the fact that these practices might involve higher costs, technical knowledge, or labor, which can be a hindrance to their adoption by small farmers.

### 3.2.1. Relationship Between CSA Adoption and Perceived Difficulty

For the assessment of the relationship between adoption and perceived difficulty, a Spearman rank correlation test was conducted based on the 30 CSA practices. The negative result ($\rho = -0.305$, $p = 0.102$) can be described in a way that difficulty undermined the adoption of CSA to some extent.

3.2.2. Quadrant Analysis of Adoption and Difficulty

To gain a deeper insight into the relationship between adoption of CSA practices and perceived difficulty of implementation, the quadrant analysis was performed by taking the average adoption index (58.13%) and average difficulty index (2.72) as the cut-off points. In this way, the CSA practices are categorized into four classes depending on the degree of adoption and implementation difficulty (Figure 2). These categories include scalable practices, highly adopted but difficult to implement practices, under-utilized but easy to implement practices, and practices needing immediate attention, respectively. The quadrant analysis helps develop an efficient strategy for extending the adoption of CSA practices.

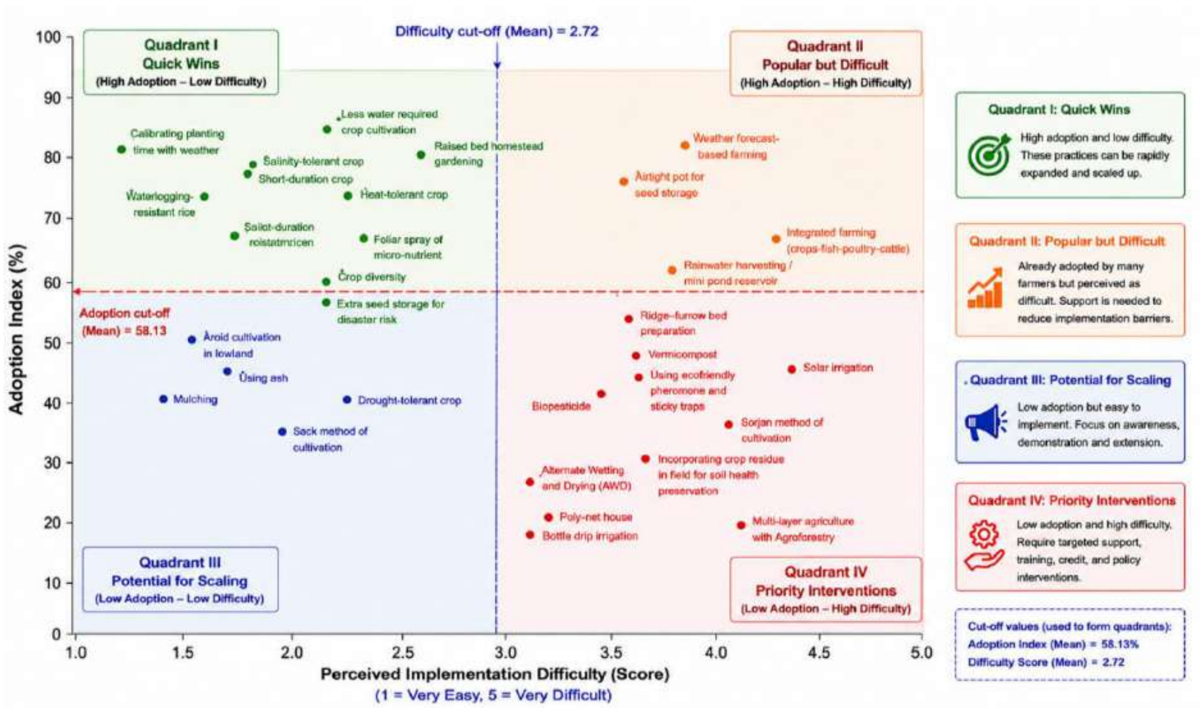


**Figure 2.** Two-dimensional matrix classifying CSA practices according to adoption level and perceived implementation difficulty among coastal farmers.

3.2.3. Quadrant I – Quick Wins

The practices found in this quadrant are already well established and are viewed as quite easy to implement. They are examples of CSA technologies that have been tested and can be quickly scaled up using standard agricultural extension services. Examples include climate-resilient planting periods, drought-resistant crops, and water-efficient cropping systems.

3.2.4. Quadrant II – Popular but Difficult

Despite being seen as difficult to adopt, these practices have been adopted by many people. The continuation in the adoption of these practices implies that farmers see huge benefits in adopting these practices. Some of these benefits include increased resilience, productivity, or livelihood security. Future efforts should emphasize reducing these adoption barriers.

3.2.5. Quadrant III – Potential for Scaling

These practices are relatively easy to adopt, but not sufficiently adopted as yet. The main barriers are likely to be lack of knowledge, poor extension effort, or inadequate demonstrations, and not technical problems. There is much potential here for rapid diffusion through communication and demonstration efforts.

3.2.6. Quadrant IV – Priority Interventions

The practices in this quadrant have low adoption and a high level of difficulty in implementation. This makes most of these practices costly to implement. It is important, therefore, that these technologies get priority in extension services, credit, subsidization, and other policies that can enhance their adoption by the farmers along the coast.

*3.3. Extension Strategies for Promoting CSA*

Table 4 presents farmers' exposure to different extension and advisory services. The most frequently accessed intervention was miking for preparedness, with 51.8% (n = 200) reporting "always" exposure. Farmers' home visits by extension officers were also common, with 43.0% (n = 166) indicating "sometimes" exposure. Training programs were moderately accessed, as 27.6% (n = 107) of respondents reported regular participation. Agricultural television programs were also relatively effective, reaching 24.2% (n = 93) of farmers regularly.

In contrast, institutionalized approaches such as Farmer Field Schools (FFS/FBS) were rarely accessed, with 57.2% (n = 221) reporting no exposure. Similarly, community radio services (69.1%, n = 267), motivational tours (66.8%, n = 259), mobile-based advisory services (55.2%, n = 214), and posters/leaflets (44.8%, n = 173) showed limited penetration.

**Table 4.** Distribution of farmers by extension strategies for promoting CSA (N = 386).

| Rank | Extension Strategies | Never n | Rarely n | Sometimes n | Regularly n | WM |
|---|---|---|---|---|---|---|
| 1 | Miking for disaster preparedness | 50 | 35 | 101 | 200 | 2.17 |
| 2 | Training on CSA | 72 | 85 | 122 | 107 | 1.68 |
| 3 | Agricultural TV program | 66 | 119 | 108 | 93 | 1.59 |
| 4 | Field day | 74 | 111 | 144 | 57 | 1.48 |
| 5 | Free fertilizer | 105 | 78 | 146 | 57 | 1.40 |
| 6 | Encouraging farmers for high-value crop cultivation | 63 | 146 | 136 | 41 | 1.40 |
| 7 | Demonstration | 80 | 114 | 150 | 42 | 1.40 |
| 8 | Farmers' home visits by extension agents | 79 | 113 | 166 | 28 | 1.37 |
| 9 | Free seed supply | 107 | 94 | 133 | 52 | 1.34 |
| 10 | Purchasing good-quality seed from farmers at a fair price | 123 | 74 | 134 | 55 | 1.31 |
| 11 | Result demonstration | 115 | 102 | 130 | 39 | 1.24 |
| 12 | Regular advisory support to commercial farmers | 102 | 148 | 83 | 53 | 1.23 |
| 13 | Free sapling supply | 120 | 105 | 130 | 31 | 1.19 |
| 14 | Agricultural fair | 111 | 126 | 123 | 26 | 1.17 |
| 15 | Incentives | 140 | 82 | 139 | 25 | 1.13 |
| 16 | Biofertilizer/Vermicompost | 157 | 80 | 107 | 42 | 1.09 |
| 17 | Group meeting/CIG | 165 | 105 | 63 | 53 | 1.01 |
| 18 | Prizing model farmer | 174 | 88 | 93 | 31 | 0.95 |
| 19 | Poster/Leaflet/Booklet | 173 | 126 | 75 | 12 | 0.81 |
| 20 | Mobile apps/Facebook | 214 | 79 | 51 | 42 | 0.80 |
| 21 | Subsidy for mechanization | 206 | 108 | 46 | 26 | 0.72 |
| 22 | Farmers' field school (FFS) | 221 | 104 | 53 | 8 | 0.61 |
| 23 | Motivational tour | 259 | 76 | 43 | 8 | 0.48 |
| 24 | Community radio service | 267 | 64 | 48 | 7 | 0.47 |

*3.4. Correlation Analysis Among Study Variables*

The Spearman correlation matrix (Table 5) reveals significant interrelationships among the key constructs (Figure A1). CSA practice adoption exhibited a strong positive association with extension strategies for promoting CSA ($\rho = 0.407$, $p < 0.01$), knowledge of CSA ($\rho = 0.427$, $p < 0.01$), extension communication ($\rho = 0.348$, $p < 0.01$), innovativeness ($\rho = 0.334$, $p < 0.01$), and ICT use ($\rho = 0.332$, $p < 0.01$). Extension communication demonstrated the strongest association with extension strategies for promoting CSA ($\rho = 0.687$, $p < 0.01$), indicating its central role in shaping adaptation behavior. Knowledge of CSA was significantly correlated with extension communication ($\rho = 0.439$, $p < 0.01$) and innovativeness ($\rho = 0.331$, $p < 0.01$). Perceptions of climate change showed weak and mixed relationships, including significant negative correlations with ICT use ($\rho = -0.223$, $p < 0.01$) and extension strategies for promoting CSA ($\rho = -0.111$, $p < 0.05$), indicating a complex attitudinal structure among farmers.

**Table 5.** Spearman's Rank Correlation Matrix among the study variables (N = 386).

| Variables | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 1. Innovativeness | 1 | | | | | | | |
| 2. Extension communication | .157** | 1 | | | | | | |
| 3. Organizational participation | .060 | .348** | 1 | | | | | |
| 4. Use of ICT | .106* | .388** | .261** | 1 | | | | |
| 5. Knowledge on CSA | .331** | .439** | .260** | .258** | 1 | | | |
| 6. Perception of climate change | .033 | −.012 | .067 | −.223** | .095 | 1 | | |
| 7. Extension strategies for promoting CSA | .252** | .687** | .298** | .505** | .349** | −.111* | 1 | |
| 8. CSA Practice Adoption | .334** | .348** | .108* | .332** | .427** | .122* | .407** | 1 |

Notes: Values are Spearman's rank correlation coefficients ($\rho$).
* $p < 0.05$, ** $p < 0.01$.

### *3.5. Structural Model Fit*

The structural equation model demonstrated an acceptable but mixed overall fit to the data (Table 6). The $\chi^2/df$ ratio was 4.653, which is within the acceptable threshold (< 5.0). Several incremental fit indices were satisfactory, with CFI = 0.945, IFI = 0.947, and NFI = 0.933, all exceeding the recommended cutoff of 0.90. However, the Tucker–Lewis Index (TLI = 0.836) fell below the acceptable threshold, suggesting partial model misspecification. The RMSEA value of 0.097 exceeded the ideal limit (< 0.08), indicating moderate approximation error. Therefore, the model should be interpreted as showing generally acceptable but mixed fit, rather than uniformly good model fit.

**Table 6.** Model Fit Indices for the Structural Equation Model (SEM).

| Fit Index | Obtained Value | Recommended Value |
|---|---|---|
| $\chi^2$ | 55.836 | - |
| df | 12 | - |
| $\chi^2$/df | 4.653 | < 5.0 acceptable |
| CFI | 0.945 | ≥ 0.90 |
| TLI | 0.836 | ≥ 0.90 |
| IFI | 0.947 | ≥ 0.90 |
| NFI | 0.933 | ≥ 0.90 |
| RMSEA | 0.097 | < 0.08 |

Note: $\chi^2$ = Chi-square; df = degrees of freedom; CFI = Comparative Fit Index; TLI = Tucker–Lewis Index; NFI = Normed Fit Index; IFI = Incremental Fit Index; RMSEA = Root Mean Square Error of Approximation; PCLOSE = p of Close Fit.

### *3.6. Structural Path Analysis*

The structural relationships shown in Table 7 suggest some important paths between extension-related factors, farmer characteristics, the perception of climate change, knowledge of CSA, and adoption of CSA practices. Extension communication was the strongest predictor of extension strategies for promoting CSA ($\beta = 0.551$, CR = 14.348, $p < 0.001$), followed by ICT use ($\beta = 0.276$, CR = 7.204, $p < 0.001$) and innovativeness ($\beta = 0.151$, CR = 4.419, $p < 0.001$). CSA practice adoption was positively associated with extension strategies for promoting CSA ($\beta = 0.328$, CR = 7.127, $p < 0.001$), knowledge of CSA ($\beta = 0.302$, CR = 6.583, $p < 0.001$), and perception of climate change ($\beta = 0.164$, CR = 3.822, $p < 0.001$; Figure 3). The observed structural pathways were found to be consistent with the proposed mediating mechanism, wherein the extension-related factors and farmer characteristics were related to the knowledge and strategic behaviors, which are, in turn, related to the adoption of the CSA practice. However, since specific indirect effects were not directly estimated, these pathways represent evidence in support of the proposed pathway, rather than evidence of a statistically established mediation effect. Interestingly, ICT use exhibited a significant negative effect on perception of climate change ($\beta = -0.200$, CR = −3.773, $p < 0.001$), indicating a potential disconnects between digital engagement and climate awareness. The associations between them were not assessed directly in the survey and need to be further investigated. The knowledge of CSA showed a positive association with the farmers' participation in organizations ($\beta = 0.133$, CR = 2.835, p = 0.005) and climate change perception (β = 0.119, CR = 2.242, p = 0.025), suggesting that collective participation may contribute to the knowledge and climate-related perceptions of the farmers.

**Table 7.** Standardized structural path estimates and covariances of the Path Model.

| Structural Path | B | β | SE | CR | p-value |
|---|---|---|---|---|---|
| Innovativeness → Knowledge on CSA | 0.149 | 0.256 | 0.025 | 5.981 | < 0.001 |
| Organizational Participation → Knowledge of CSA | 0.699 | 0.133 | 0.247 | 2.835 | 0.005 |
| Extension communication → Knowledge of CSA | 0.298 | 0.395 | 0.035 | 8.413 | < 0.001 |
| Innovativeness → Extension strategies for promoting CSA | 0.232 | 0.151 | 0.053 | 4.419 | < 0.001 |
| Extension communication → Extension strategies for promoting CSA | 1.102 | 0.551 | 0.077 | 14.348 | < 0.001 |
| Use of ICT → Extension strategies for promoting CSA | 0.827 | 0.276 | 0.115 | 7.204 | < 0.001 |
| Organizational Participation → Perception of Climate Change | 0.634 | 0.119 | 0.283 | 2.242 | 0.025 |
| Use of ICT → Perception of Climate Change | −0.229 | −0.200 | 0.061 | −3.773 | < 0.001 |
| Knowledge of CSA → CSA Practice Adoption | 0.647 | 0.302 | 0.098 | 6.583 | < 0.001 |
| Extension strategies for promoting CSA → CSA Practice Adoption | 0.264 | 0.328 | 0.037 | 7.127 | < 0.001 |
| Perception on Climate Change → CSA Practice Adoption | 0.346 | 0.164 | 0.090 | 3.822 | < 0.001 |

Note: β = standardized regression coefficient; SE = standard error; CR = critical ratio; p-values are reported as two-tailed significance levels. Structural paths represent directional effects (→), while covariances between exogenous variables are indicated by (↔). All reported associations are statistically significant at p < 0.05.

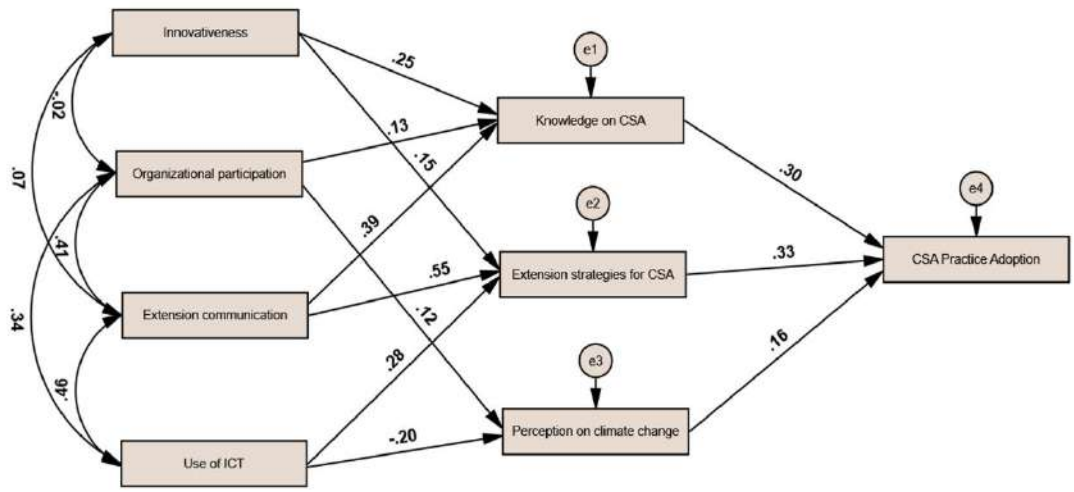


**Figure 3.** Path analysis model.

### *3.7. Correlations Among Exogenous Variables*

Table 8 shows significant interrelationships among exogenous variables. Extension communication was strongly associated with ICT use (CR = 8.204, p < 0.001) and organizational participation (CR = 7.407, p < 0.001). Similarly, ICT use and organizational participation were positively correlated (CR = 6.250, p < 0.001).

**Table 8.** Correlations among Exogenous Variables of the study.

| Variables | Estimate | SE | CR | p-value |
|---|---|---|---|---|
| Innovativeness ↔ Extension communication | 0.067 | 2.189 | 1.472 | 0.141 |
| Innovativeness ↔ Organizational Participation | −0.021 | 0.333 | −0.448 | 0.654 |
| Extension communication ↔ Use of ICT | 0.458 | 1.392 | 8.204 | <0.001 |
| Extension communication ↔ Organizational Participation | 0.406 | 0.293 | 7.407 | <0.001 |
| Use of ICT ↔ Organizational Participation | 0.335 | 0.191 | 6.250 | <0.001 |

## 4. Discussion

This study aimed to understand the factors affecting the adoption of climate-smart agriculture (CSA) by coastal farmers, including socio-demographic factors, extension services, ICT use, organizational participation, knowledge, climate change perception, and innovativeness within the framework of structural equation modeling. The results suggest that CSA adoption is a complex phenomenon, and knowledge, innovativeness, exposure to extension, and participation in organizations of farmers are the most important factors influencing CSA adoption, and the adoption of capital-intensive CSA technologies is still limited by a lack of institutional and financial support. Moreover, the findings underscore the need to enhance agricultural extension, farmer groups, and knowledge-sharing mechanisms to facilitate the adoption of climate-smart farming practices.

This study finds that the majority of farmers in middle age group and above are involved in farming with moderate education and less exposure to formal training. This is commonly observed in smallholder agriculture where there are aging farm populations, which often limit the adoption of climate-smart innovations because of lower risk appetite and decreased adoption of new technologies (Atta-Aidoo et al., 2022; Khatri-Chhetri et al., 2017). Education is identified as a critical enabler-farmers with more education can process climate information and implement adaptive strategies. These findings align with a recent study, which also indicates that education plays a vital role in increasing the adoption of agricultural technologies by strengthening cognitive abilities and the use of information resources (Oli et al., 2025). Small farmers also dominate, making structural constraints even more pronounced. Small farm size reduces the scope for economies of scale and deters capital-intensive CSA technologies, as is well documented in the empirical adoption studies from Asia and Sub-Saharan Africa (Barasa et al., 2021; Naveen et al., 2024).

The adoption-difficulty matrix descriptively suggests that farmers are more likely to adopt CSA practices that are easier to implement, while technically demanding and resource-intensive practices remain less widely adopted (Zheng et al., 2024). The findings clearly indicate that low-cost adaptive practices and capital-intensive climate-smart technologies are different. Adoption of irrigation technologies and protected cultivation is limited, and farmers prefer to adopt practices like crop diversification, tolerant varieties, planting time adjustment, and improved storage systems. This adoption gradient is a rational risk minimization response to climate uncertainty. The same pattern has been observed among coastal farmers in Bangladesh, where limited economic resources and the risk of exposure to climate change deter them from investing in transformative adaptation measures (J. R. Sarker et al., 2026). The low adoption rates of technologies like AWD irrigation, drip systems, etc., indicate that barriers to diffusion are not only a lack of awareness but also a lack of credit access, infrastructure constraints, and poor input-output market linkages. The findings align with the empirical literature, which demonstrates that a firm's decision to adopt CSA is heavily influenced by its liquidity and institutional support mechanisms (Billah et al., 2025; Ulucak et al., 2026).

The study emphasizes the need to strengthen and expand the use of traditional extension methods (miking, home visits, etc.) and institutionalized methods (Farmer Field Schools, mobile advisory services, etc.). This pattern may reflect a continuing "last-mile delivery gap" in agricultural extension systems, whereby information is available but not effectively disseminated to farmers through formal institutional channels. The same has been reported in research indicating the effectiveness of interpersonal extension over digital tools for areas with low digital literacy and poor ICT infrastructure (Aslam, 2025; Fabregas et al., 2019). The poor uptake of Farmer Field Schools is especially relevant since they have been demonstrated to have a significant impact on adoption of sustainable agriculture practices when applied effectively (Ongachi et al., 2026; Waddington et al., 2012).

The results of this study also find that knowledge, innovativeness, use of ICTs, and exposure to extension are the most interdependent factors associated with CSA adoption. According to the knowledge-attitude-practice model, the acquisition of knowledge is a prerequisite for attitudinal and behavioral change, and knowledge of CSA appears to represent an important intermediary pathway linking farmers' characteristics with CSA adoption (Kifle et al., 2022). Innovativeness is also strongly associated with CSA adoption, which supports diffusion theory that early adopters facilitate technology uptake in rural systems (Colton, 2015). The strongest determinant of extension strategies for promoting CSA is extension communication, which suggests that multi-channel information dissemination is important. This is consistent with the results of other studies that have highlighted the positive effects of exposure to various communication channels on adaptive decision-making and the reduction of information asymmetry (Oyelami et al., 2022; Wang et al., 2026).

Furthermore, in the structural model, the use of ICTs was negatively related to a perception of climate change. This indicates that digital exposure does not necessarily lead to increased awareness or perception of the farmers regarding climate change. One potential explanation is that the information provided via digital channels may not be of the same quality, accuracy, or local relevance, although these mechanisms were not explicitly examined in this study. This finding could therefore be interpreted as evidence for a possible "digital paradox" that more digitization does not necessarily lead to more climate awareness or adaptive orientation (Gumbi et al., 2023; Matsvai & Hosu, 2024). The relationship between the availability of agricultural and climate information via digital platforms and the negative association needs to be understood further, which can be done by studying the type, source, quality, and utility of the information in the local context.

There is a strong link between organizational participation and knowledge and perceptions of climate, highlighting the importance of social capital in agricultural adaptation. Farmer groups enable joint learning, lower transaction costs, and improve access to extension services. This is in line with empirical evidence that social networks and collective action institutions play a key role in the adoption of agricultural innovations, especially in risk-prone environments (Husen et al., 2017; Ma et al., 2023).

Furthermore, the adoption of CSA is a result of the interplay between individual attributes, institutional structures, and information flows. The observed interrelationships among extension exposure, ICT use, and organizational participation are consistent with the possibility of mutually reinforcing information and institutional processes within an agricultural innovation system (AIS). This aligns with the Agricultural Innovation Systems (AIS) approach that views adoption as a process of dynamic interaction between actors, institutions, and technologies (Gutiérrez et al., 2023). The results also suggest that disjointed extension systems can lead to inequalities in access to climate information, further exacerbating adoption gaps.

*Limitations of the Study and Future Directions*

This study has demonstrated several strengths, including multistage random sampling and a structural framework for CSA adoption. The use of path analysis enabled the simultaneous examination of the hypothesized structural relationships among the study variables, including direct pathways specified in the model. There are a few limitations to be noted, too. First, specific indirect effects were not directly estimated; the degree to which mediation can be formally established is also limited. Secondly, the model is directed, yet the cross-sectional design does not allow for causal inference. Third, TLI and RMSEA were not within the standard range (e.g., TLI > 0.95, RMSEA < 0.05), indicating some model mis-specification. Lastly, sampling was limited to one upazila per district, and financial and credit-access variables, although discussed, were not formally included in the structural model, thus reducing the generalizability and explanatory range.

## 5. Conclusions

The current study has shown that adoption of CSA by coastal farmers in Bangladesh is a complex phenomenon, which occurs because of the cumulative effect of various factors, namely extension communication, institutional participation, knowledge of farmers, innovativeness, and climate change perception, instead of being determined by a particular factor. Farm households are willing to adopt low-cost and low-risk techniques that bring immediate results, but advanced technologies are underutilized because of existing obstacles of an institutional, financial, and infrastructure nature. The observed pathways involving extension communication, CSA knowledge, and extension exposure highlight the importance of effective dissemination and knowledge-development mechanisms, including interpersonal and community-based approaches like farmer field schools and home visits, in order to overcome the "last-mile" problem of agricultural extension. In turn, the negative relationship between ICT usage and climate change perception reveals that increased access to digital technologies is not enough for creating the climate awareness of farm households and their readiness for adaptation, and high-quality CSA related location specific content needs to be delivered as well.

The above findings point out to the need for an integrated policy framework that integrates extension services, farmer organizations' empowerment, credit and inputs provision for high difficulty technologies, and ICT strategies to promote adoption of CSA among vulnerable coastal areas. The idea here is to move farmers from making small changes to adopting a transformational model of agriculture. Longitudinal studies are needed to confirm the directional pathways identified in this study, particularly the extension-knowledge-adoption pathway. Future research should also examine the quality and credibility of information disseminated through specific digital platforms to better understand the mechanisms underlying digital communication. Additionally, policymakers should promote the adoption of capital-intensive climate-smart technologies, such as poly-net houses and solar irrigation systems, through targeted financial support, training, and extension services.

**CRediT Author Statement: Md. Sumon Howlader:** Conceptualization, Methodology, Investigation, Data curation, and Writing – original draft; **Md. Mamun-Ur-Rashid:** Supervision, Writing – review & editing, and Validation; **Md. Kamrul Hasan:** Supervision, Writing – review & editing, and Validation; **Md. Ektear Uddin:** Conceptualization, Supervision, and Writing – review & editing.

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### Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CSA | Climate-smart Agriculture |
| ICT | Information and Communications Technology |
| AIS | Agricultural Innovation Systems |
| FFS | Farmer Field Schools |
| FBS | Farmers Business School |
| DS | Difficulty Score |
| SAAO | Sub-Assistant Agriculture Officers |
| AI | CSA Adoption Index |
| WM | Weighted Mean |
| MS | Maximum Possible Score |
| RMSEA | Root Mean Square Error of Approximation |
| CFI | Comparative Fit Index |
| TLI | Tucker–Lewis Index |
| IFI | Incremental Fit Index |
| MSV | Maximum Shared Variance |
| $\chi^2$ | Chi-Square Statistic |
| SE | Standard Error |
| Df | Degrees of Freedom |
| CR | Critical Ratio |
| $\beta$ | Standardized Regression Coefficient (Beta Coefficient) |
| $R^2$ | Coefficient of Determination (Explained Variance) |

**Appendix A**

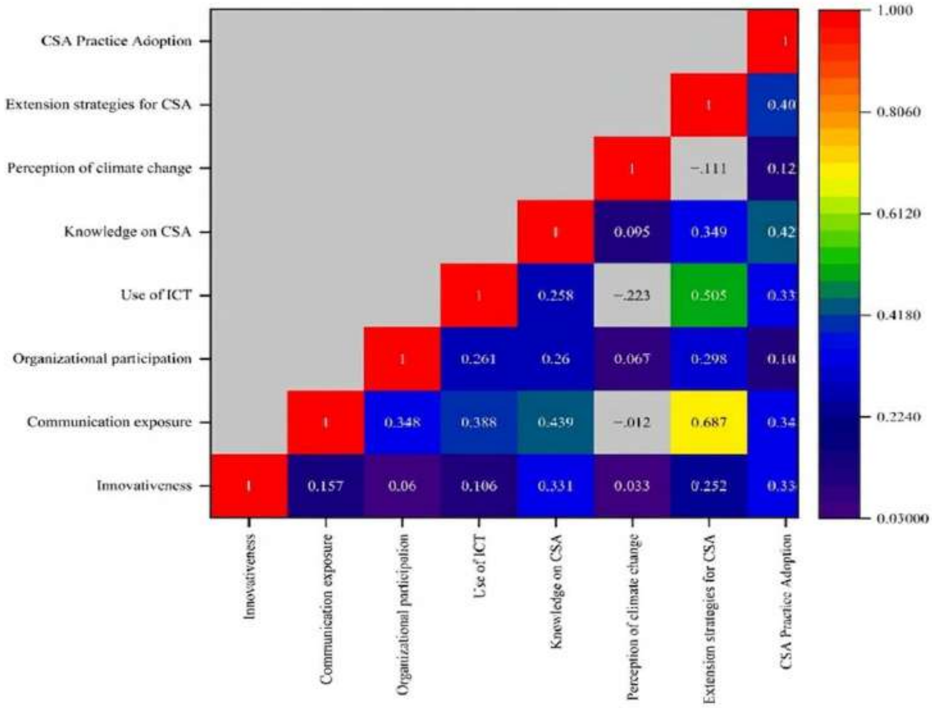


**Figure A1.** Correlation matrix among variables.

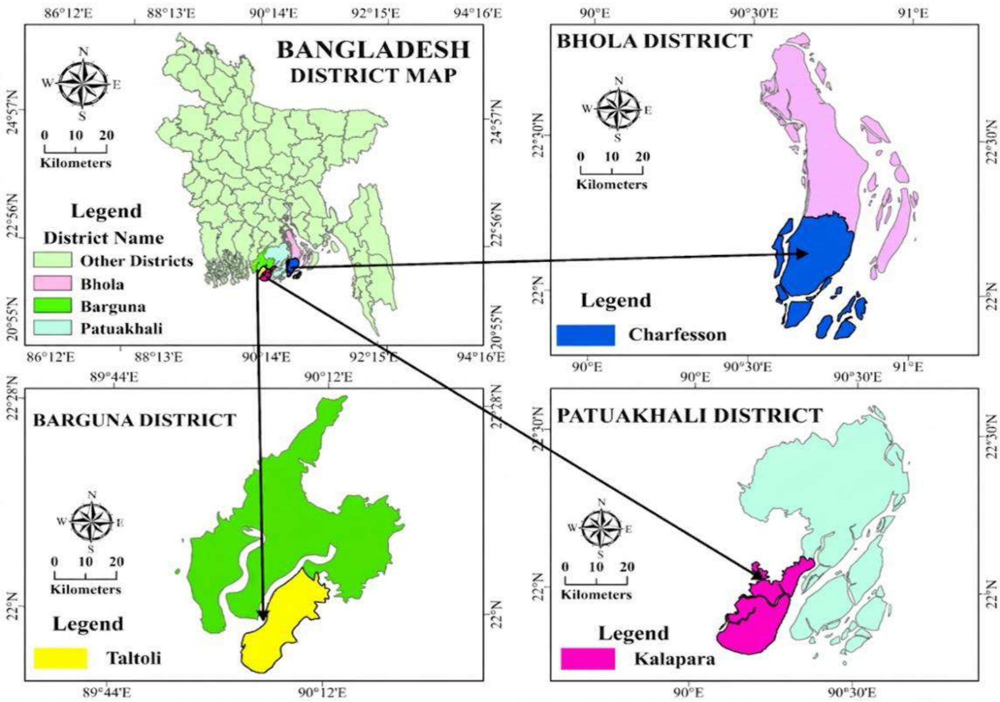


**Figure A2.** Map showing the study area.

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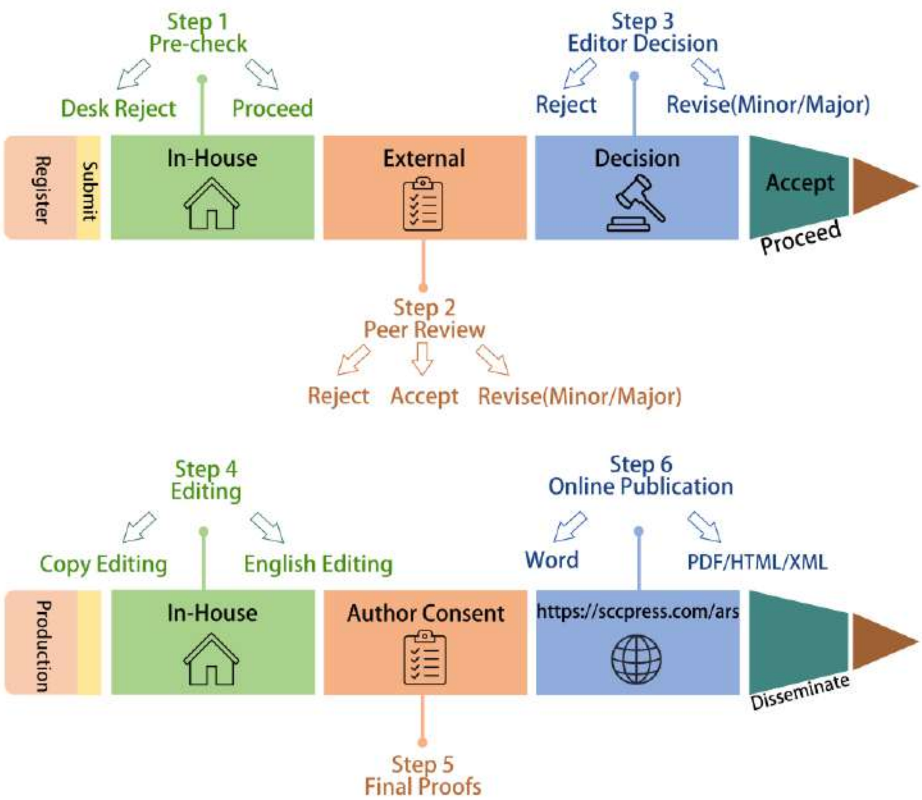

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