03, 2025
Volume 3 Issue 1

Agricultural & Rural Studies

EDITOR-IN-CHIEF:JUNBIAO ZHANG

ISSN 2959-9784
9 772959 978259 01 >
SCC PRESS
https://sccpress.com/ars
OPEN ACCESS
ISSN 2959-9784

Cover Story

After World War II, the agrarian policy in the former Yugoslavia differed significantly from other socialist countries. Mass collectivization of land was not carried out following the Soviet model, because it faced serious problems in food production. However, state ownership remained dominant until the collapse of the country during the 1990s.
Nevertheless, at the beginning of the period of transition from socialism to capitalism, individual agriculture was dominant (in terms of the extent of use of arable land), but, in relation to the state sector, its production for some time remained significantly extensive and less market oriented.
After the year 2000, Serbia as a new country began to be included in international political and economic flows. The development of individual agricultural holdings started to accelerate and soon this type of agricultural organization became the carrier of the development of the whole Serbian agriculture. It was primarily the case within the fruit growing and viticulture sectors, where relatively small individual farms started to introduce the new trends.
Today, apple production, as one of the most intensive areas of fruit production in general, occupies a special place in Serbia, and especially in its northern province of Vojvodina, Thanks to the encouraging agricultural policy, but also to the new possibilities of export, there began an expansion of apple orchards with the modern assortment. The full application of agrotechnical measures, based on the Austrian-Italian model, and the developed consultancy, have made this branch of plant production one of the most common and most competitive in today's Serbian agriculture.
(Prof. Dr. Aleksandar Čučković, Dean of Faculty of Economics in Subotica, University Of Novi Sad, Subotica, Serbia.)

Agricultural & Rural Studies

Vol. 3, No. 1 March, 2025

Contents

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.

Core Features:

(1) **Interdisciplinary Scope:** A&R centers on interdisciplinary and multidisciplinary inquiry, integrating insights from economics, sociology, human geography, and cognate disciplines to address pressing contemporary issues in agriculture, rural development, and farmer-related policies—bridging theoretical frameworks to advance holistic understandings of these dynamic systems.

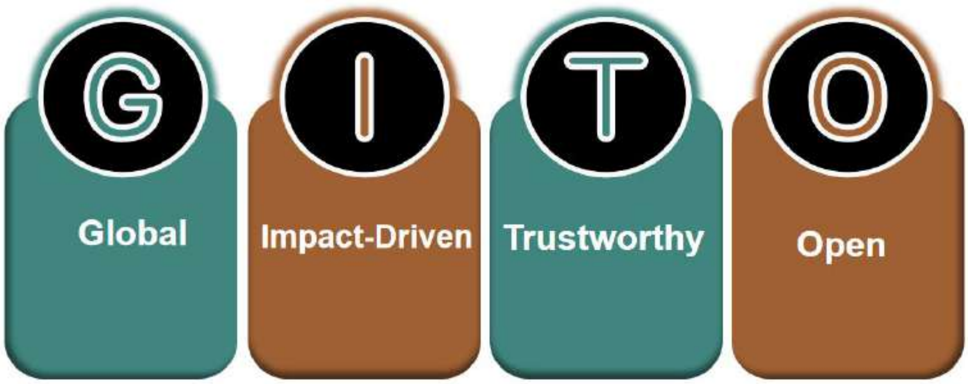
(2) **Global Editorial Excellence:** The journal is guided by a distinguished, highly specialized, and globally diverse editorial board, ensuring rigorous peer review, cultural sensitivity, and alignment with international scholarly standards.

(3) **Culture-Driven Operations:** Rooted in our mission, vision, and values, cultural stewardship lies at the core of A&R's identity. Our unwavering commitment to ethical principles, community engagement, and purposeful impact permeates every facet of the journal's operations.

(4) **Sustainable Non-Profit Model:** No Article Publishing Charges (APC) for the first four years. Beyond this, it will maintain a reasonable level of APC for authors worldwide in the future.

(5) **Fully Independent OA Platform:** As an independent OA publication (https://sccpress.com/ars), A&R prioritizes equitable global access to scholarship while actively promoting your work to a worldwide audience, maximizing its reach and impact.

(6) **Tailored Publication Support:** Committed to fostering a seamless research journey, A&R offers comprehensive, efficient, and professional editorial services. Recognizing the unique demands of each study, our dedicated team provides structured guidance—from refining article frameworks to managing references—simplifying the publication process and empowering authors to focus on their core scholarship.



Agricultural & Rural Studies

Article

Feminist Agroecology: Towards Gender-Equal and Sustainable Food Systems in Sub-Saharan Africa

Michaelin Sibanda [1]

1 Lund University Centre for Sustainability Studies, Lund University, Lund Box 117, SE-22100, Sweden; michaelin.sibanda@lucsus.lu.se

Abstract: Agriculture is pivotal in the global economy but is challenged by unsustainable practices that harm the environment and aggravate social inequalities, particularly in sub-Saharan Africa (SSA). Women, making up half the agricultural workforce, often do not benefit equitably from their labour due to systemic gender inequalities. Applying a Feminist Political Ecology (FPE) lens reveals the unequal gendered power dynamics that influence access to resources, decision-making, and the distribution of benefits within agricultural value chains. In a narrative literature review, I integrate FPE principles with agroecological approaches to address gaps in understanding gender dynamics within food systems and highlight positive outcomes from integrating FPE, such as improved crop diversity, food security, and economic stability, while acknowledging challenges like entrenched gender norms, intersecting inequalities, and resistance to change. I explore how gender-sensitive agroecology can promote sustainable and equitable food systems and examine how patriarchal systems marginalize women in agriculture, restricting their access to resources and decision-making. The analysis asserts ongoing debates around the scalability of gender-sensitive agroecological approaches and the challenges of implementing FPE insights within existing policy frameworks. Identified gaps include the need for more longitudinal studies on the impacts of FPE-informed interventions and greater attention to women's diverse experiences across different agroecological zones. Overall, this review contributes to academic discourse and policy discussions, seeking to advance a critical understanding of gender equality and sustainable agriculture in smallholder farming.

Keywords: agroecology; feminist political ecology; gender equity and equality; sustainable food systems; sub-Saharan Africa; smallholder farmers

Citation: Sibanda, M. (2025). Feminist Agroecology: Towards Gender-Equal and Sustainable Food Systems in Sub-Saharan Africa. *Agricultural & Rural Studies*, *3*(1), 16. https://doi.org/10.59978/ar03010001

Received: 1 August 2024
Revised: 18 September 2024
Accepted: 12 November 2024
Published: 21 February 2025

1. Introduction

Agriculture sustains millions of farmers globally, yet it is plagued by practices that undermine both the environment and social equality, not the least among smallholders in sub-Saharan Africa (SSA) (Food and Agriculture Organization of the United Nations [FAO], 2023). Sustainable food systems, which aim to balance food production with environmental protection and social equity, are especially critical in SSA, where agriculture supports a significant portion of the population. These systems integrate ecological principles, such as crop diversity and soil health, with social dimensions like equitable access to resources and gender equality (Amede et al., 2023). In SSA, the agricultural sector is integral to the global economy, accounting for approximately 15-20% of the GDP and supporting 70–80% of employment, primarily among smallholder farmers (Solomon et al., 2024). The typical food systems are characterized by their diversity and reliance on smallholder farmers, who produce the majority of the region's food. However, these systems often depend on rain-fed agriculture, making them vulnerable to climate variability. Despite the inherent diversity of SSA's food systems, smallholder farmers face numerous challenges that hinder their productivity and market access (Solomon et al., 2024). These barriers are exacerbated by gender inequalities, as women, who play crucial roles in food production, often lack access to resources and decision-making opportunities (Wezel et al., 2020). Addressing these challenges is essential for fostering sustainable and inclusive agricultural practices that can mitigate both environmental and social inequities in the region (Zaremba et al., 2021).

However, the dominant model of industrial agriculture, characterized by extensive monocultures, agrochemical-intensive practices, and large-scale operations, contributes to environmental degradation and biodiversity loss (Tscharntke et al., 2021). This model disproportionately benefits large, resource-rich farmers, marginalizing smallholders—particularly women—who face restricted access to land, credit, and other resources (Manji, 2020). This exacerbates existing gender inequalities, pushing women, who play a crucial role in SSA's agricultural systems, further to the economic margins (Wezel et al., 2020). Despite the recognized need for sustainable and inclusive agricultural practices, much of the existing research focuses broadly on agroecological benefits without adequately addressing the gender dynamics within these systems. Additionally, while there are review studies on sustainable agriculture, many are outdated and do not reflect recent developments in both FPE and agroecology, particularly in the context of SSA (Zaremba et al. 2021). These studies often overlook gender dynamics and the evolving focus on social equity and environmental sustainability in the region. This represents a significant research gap, especially regarding how systemic gender inequalities shape women's access to, use of, and control over agricultural resources and decision-making power.

Recent debates on agricultural development continue to focus on balancing productivity with sustainability and social equity. For example, Ajibade et al. (2023) advocate for the commercial intensification of agriculture to promote food security, while Foley et al. (2011) emphasize the importance of agroecological practices that support smallholder farmers. However, these discussions often overlook how gender-sensitive approaches could play a transformative role in achieving both sustainability and equity. In particular, the intersection of gender and agroecology remains underexplored, especially in terms of how gender dynamics shape access to resources and decision-making within agricultural systems, leaving a critical gap in understanding the potential of feminist political ecology (FPE) to address these issues. Women in SSA's farming communities, who make up a substantial portion of the agricultural workforce and play key roles in production and biodiversity management, continue to face systemic barriers that limit their access to resources and decision-making agencies (Manji, 2020; Solomon et al., 2024). Addressing these gender imbalances is essential not only for women's empowerment but also for the broader sustainability and equity of food systems.

In this study, I aim to integrate FPE with agroecology to critically examine and address these gender inequalities within agricultural systems. Unlike previous studies that either overlook gender or focus on isolated issues, this review explores how gender and FPE intersect with agroecological practices. By effectively addressing the systemic gender imbalances and economic injustices prevalent in current food production systems (Elmhirst, 2017), this approach provides a promising avenue for transforming agricultural systems to be both equitable and sustainable. Embedding gender considerations into the fabric of agroecological strategies can challenge and reshape unequal socio-economic structures and gender dynamics constraining equitable and sustainable food systems while advancing gender equality (Zaremba et al., 2021). This article argues that this integration enhances the sustainability of agricultural systems and promotes gender equity by addressing the power dynamics and intersectional issues that affect women farmers. This approach can potentially transform food systems to be both environmentally sustainable and socially just by leveraging women's local ecological knowledge and advocating for policy support. Following that, this research seeks to provide actionable insights and policy recommendations for promoting gender-responsive and sustainable agricultural practices in SSA.

The study is designed as a narrative literature review, where I lay out the theoretical foundations of FPE and show how it is practiced in agroecological contexts. In doing so, I explore various dimensions of FPE, including its critique of traditional ecological and agricultural approaches that often marginalize gender considerations. I will also discuss how FPE can provide a lens for understanding the intersectionality of gender with other forms of social and economic power, such as class and race/ethnicity, and their cumulative impact on agricultural productivity and ecological sustainability. I go beyond merely highlighting problems, focusing on proposing solutions through case studies and empirical evidence demonstrating the viability and benefits of incorporating FPE into agroecology. I will conclude with policy recommendations aimed at scholars interested in agroecology to pay attention to the gendered nature of agricultural development.

2. The Feminist Political Ecology Framework

Political Ecology (PE) is a multidisciplinary domain/field that explores how unequal power dynamics and associated narratives influence the construction, expression, experience, and generation of human-environment interactions (Sultana, 2021). Originating in the 1970s as a response to a politically neutral ecology that treats nature as a static entity, PE offers insights into how politics and power influence environmental changes and resource management over time and space (Forsyth, 2004; Sultana, 2021). It examines how different groups access and control resources, negotiate their use or resist unfavorable policies and relations of power (Zimmerer, 2006). Moreover, PE explores the role of activism and social movements in challenging injustices, promoting alternative development, and influencing environmental outcomes (Rocheleau, 2008).

Building on the principles of PE, FPE emerged in the 1990s and draws inspiration from academic disciplines such as anthropology, critical development studies, and political economy, which examine power dynamics within socio-ecological relationships and research practices (Harcourt et al., 2023). It is influenced by feminist theories like ecofeminism, feminist environmentalism, feminist science studies, post-colonial feminist critiques of development, and post-structural critiques of political ecology (Mohanty, 2003; Rocheleau et al., 1996; Sultana, 2021). FPE adopts the feminist concept of intersectionality to move beyond a singular focus on women and/or gender binaries (Cho et al., 2013). In doing so, it draws attention to the complexities of multiple intersecting inequalities such as race, gender, class, ethnicity, religion, sexuality, age, and geographical location within specific landscapes (Mollett, 2017; Sultana, 2021).

FPE provides a nuanced understanding of resource access and control, resource governance, gendered knowledge, and local ecological gender conflicts within broader political and economic contexts (Lau, 2020; Susial-Martin, 2017). It emphasizes the consideration of multiple dimensions of power and social structures that influence environmental interactions, advocating for more inclusive and equitable environmental policies and practices. FPE has been employed in various fields, including environmental studies, development studies, and political ecology, to address the intersection of gender, environment, and socio-economic issues (Elmhirst, 2011). It provides a critical lens to examine how gendered power relations influence environmental management, resource access, and social justice outcomes (Sultana, 2021). This approach has been particularly influential in understanding the dynamics of environmental degradation, capitalist accumulation, and control over resources, especially in the Global South. Having set out briefly how FPE builds upon the PE and its core concepts of gendered power relations (gender, power, subjectivity) across scales and intersectionality, I move on to outline three key traits of FPE that make it particularly suited to address gender disparities in agriculture.

2.1. Gendered Power Relations and Intersectionality

As a theoretical framework, FPE explores how gendered power relations are historically constructed and organizes resource governance and social justice outcomes, and how these intersect with other forms of domination including race and class. It is used to examine the gendered nature of environmental knowledge, rights, and practices, as well as the existence of gendered environmental movements and collectives (Rocheleau & Nirmal, 2015). It addresses how gender inequalities intersect with environmental issues and how individual experiences are linked to broader socio-political and economic structures, impacting resource access, decision-making processes, and environmental outcomes (Rocheleau et al., 2016).

Initially, FPE aimed to critique mainstream PE scholarship for ignoring gendered power dynamics in environmental struggles (Sultana, 2021). This is evident in the work of the La Via Campesina and Zimbabwe Smallholder Organic Farmers Forum (ZIMSOFF), which advocates for the rights of smallholder farmers and promotes food sovereignty while facilitating grassroots networking among women leaders in environmental initiatives. The organizations challenge existing power dynamics within global agriculture and empower women to lead community-based solutions, thereby reshaping resource governance through a gender-sensitive lens (Wiebe, 2023). This empowers local communities, particularly women, to take control of their agricultural practices and land. These initiatives not only address immediate ecological challenges but also foster long-term social justice by enhancing the leadership capacities and rights of women within their communities.

FPE's framework is comprehensive, enabling a deeper analysis of patriarchy and other power structures to examine power and oppression dynamics. However, gender remains a fundamental aspect of differentiation in societies and within FPE scholarship (Sultana, 2021). Thus, feminisms address more than just "women's issues," focusing broadly on social justice and decolonizing gender and other social relations. One of the strengths of approaches informed by FPE is that they encourage a focus on how gender and other power dynamics, both between men and women and among women themselves, intersect to shape access to and control over resources or property in specific locations (Sato & Alarcón, 2019). These approaches highlight the gendered nature of intersecting power relations that connect humans and natural environments across multiple scales.

In this context, FPE emphasizes the importance of an intersectional approach, which acknowledges how gender and other forms of power interact (Tavenner et al., 2022), and how identities (such as gender, class, ethnicity, and race) and social ranks intersect to shape individuals' experiences and position in agricultural settings. This is crucial for addressing diverse community needs and tailoring inclusive and effective interventions. In SSA, women often face numerous disadvantages due to their intersectional identities, influenced by gender, class, race, ethnicity, and colonial legacies. These factors shape their access to resources, roles in agriculture, and vulnerability to environmental changes (Santpoort et al., 2021). Understanding these layered inequalities is essential for developing effective environmental policies and interventions sensitive to the nuanced needs of different community groups. FPE acknowledges the complex connections between various forms of oppression and privilege, leading to an in-depth analysis of how these intersecting factors influence human-environment relationships.

Recognizing the multifaceted nature of these power dynamics, the FPE also embraces collective action as a tool for advancing gender equality within agroecology, highlighting the significant benefits such approaches offer, including enhanced knowledge sharing and learning. In so doing, FPE has renewed interest in commons and commoning, focusing on collective action and transformative politics (Clement et al., 2019). A practical example of this is the Green Belt Movement in Kenya, initiated by Wangari Maathai. This movement involved women in tree planting to combat deforestation and promote sustainable livelihoods, effectively illustrating how collective action can lead to significant environmental and social transformations (Hunt, 2014). Through these activities, women restored ecological health by planting millions of trees and empowered themselves politically and economically, embodying the transformative politics central to FPE. However, FPE approaches often leave the concepts of common and commoning undefined. Additionally, while FPE acknowledges the commons as a contested resource, it seldom recognizes the central role of commons in community formation or considers common resources and property beyond their biophysical aspects (Sato & Alarcón, 2019).

2.2. Commitment to Equity and Justice

Central to FPE are its commitments to equity and justice, critically exploring how power dynamics are rooted in the intertwined histories of colonialism, patriarchy, capitalism, development, and the interconnected oppressions and injustices arising from these systems (Sundberg, 2017). FPE critiques traditional ecological and agricultural approaches that often marginalize gender considerations and emphasizes the importance of addressing social justice issues to enhance agricultural sustainability.

FPE critiques traditional agroecological approaches for often ignoring gender dynamics and power imbalances. These traditional practices, which include knowledge, practices, and beliefs passed down through generations, are deeply rooted in community-agroecosystem relationships and form the basis for resilient farming systems, especially against climate change (Altieri et al., 2015). FPE addresses social justice issues and aims to enhance agricultural sustainability by integrating feminist theories. This framework exposes the gendered dimensions of environmental risks, rights, and responsibilities, showing how gender inequalities intersect with environmental issues (Lawhon et al., 2013). Moreover, it links individual experiences to broader socio-political and economic structures, exploring how gendered power relations impact resource access, decision-making processes, and environmental outcomes (Nightingale, 2006). FPE highlights often-overlooked aspects, which promote a nuanced understanding of environmental dynamics, emphasizing gendered impacts and methods of survival, management, and resistance against environmental challenges. This critique is essential for promoting gender equity in agriculture by ensuring that women's roles and knowledge are recognized and valued in sustainable farming practices.

Building upon this critique, FPE shifts the focus to the embodied everyday experiences of nature-human interactions and how they manifest in various spatial contexts (Elmhirst, 2015; Rocheleau & Nirmal, 2015). It acknowledges women as active contributors, often overlooked in historical analyses (Kansanga et al., 2019), and examines how gender influences access to knowledge, space, and resources. FPE values the local ecological knowledge held mainly by women, who are often primary caretakers of biodiversity and have deep insights into resource management and sustainable practices (Rocheleau & Nirmal, 2015; Shiva, 1992). This local knowledge includes techniques for soil fertility, seed preservation, and water management, crucial for sustainable agriculture. Women's traditional ecological knowledge significantly contributes to the resilience and adaptability of food systems amid environmental change (FAO, 2011). Elias et al. (2021) highlight how an FPE approach can foster a deeper understanding of the "politics of knowledge" by meaningfully acknowledging and validating diverse forms of knowledge, including the knowledge and lived experiences of resource users, particularly women, who have been historically marginalized and silenced. Incorporating local knowledge into mainstream agroecological practices challenges the dominant scientific paradigms that overlook or undervalue indigenous wisdom. This integration enriches ecological research and fosters more sustainable and culturally appropriate farming techniques.

2.3. Equitable Resource Governance and Distribution

Gender disparities and the promotion of sustainable livelihoods are critical issues that need addressing by examining the gendered political economy and its impact on resource management. Advocating for a fairer distribution of rights and responsibilities, scholars in FPE explore how gender dynamics influence agricultural practices, including community-supported agriculture, to empower women in sustainable food systems. This scholarship and the practices it informs advocate for equitable access to land and other agricultural inputs for women, which are essential for sustainable development (Bryan et al., 2024). Differential access to resources like land, water, seeds, and credit is often structured by patriarchal norms, marginalizing women's roles, and contributions

(Santpoort et al., 2021). Policies that recognize and address these inequalities are crucial. For example, reforms in land ownership laws to ensure women's rights to land, better financial services for women, and support for women's agricultural collectives are essential steps toward gender equity in agriculture.

Moreover, the application of an intersectional approach is crucial in addressing disparities in resource governance. This approach reveals how historical discrimination and multiple power structures combine to perpetuate social disadvantage and unequal distribution of resources in ways that differ for specific women according to their social locations (Jost et al., 2015). Understanding these compounded disadvantages can lead to the development of more inclusive agricultural policies that meet the specific needs of diverse community groups.

As we consider the implications of FPE in addressing gender disparities and promoting sustainable livelihoods in agriculture, it becomes clear that a fundamental shift in our approach to farming is necessary. This brings us to the concept of agroecology as an alternative to the current industrial agricultural model. How can the transition to agroecology, which aligns closely with the principles of the FPE, be leveraged to create a more holistic, sustainable, and socially just approach to food production in the future? Exploring this question could provide valuable insights into transforming our food systems to better address gender disparities and achieve sustainable livelihoods.

3. Methodology

In this literature review, I employ a narrative synthesis approach to explore how FPE perspectives have been integrated into agroecology in SSA, specifically examining how the FPE lens addresses social justice and gender dynamics within agroecology. Narrative synthesis is a form of knowledge synthesis that summarises and interprets a wide range of studies on a given topic, offering an overview alongside critical analysis and interpretation (Sukhera, 2022). This method relies on a detailed search and analysis strategy, utilizing both academic and practitioner-oriented literature. This dual focus allows me to identify theoretical gaps and propose practical solutions, ensuring that my contributions are both academically significant and practically relevant. I searched for academic sources through databases like JSTOR, Web of Science, and Google Scholar, which are recognized for their extensive collections of scholarly resources (Gusenbauer & Haddaway, 2020). JSTOR contains archives of foundational studies, Web of Science offers citation indexing to ensure high-quality and relevant articles, and Google Scholar provides access to a wider range of multidisciplinary sources. These databases house the most current and pertinent journals on feminist political ecology, agroecology, and gender dynamics in agriculture, all of which are essential for this study.

The search terms – "agroecology," "feminist political ecology," "gender dynamics in agriculture," and "sustainable food systems in Sub-Saharan Africa" - were selected to capture the critical intersections of gender and sustainability in agricultural practices. These keywords aim to identify research that explores gendered power relations in agriculture, which is pivotal to understanding the role of women in agroecological systems. They also ensure the inclusion of studies that address sustainability and equity within SSA's unique socio-economic and environmental contexts. The focus is on peer-reviewed articles and book chapters published between 2000 and July 2024, capturing the latest trends in the field. Agroecology emerged as a transdisciplinary, participatory, and action-oriented approach in the early 2000s, gaining significant traction. A pivotal moment came with the first International Forum on Agroecology in Nyéléni, Mali, in 2007 ("Declaration of the International Forum for Agroecology, Nyéléni, Mali: 27 February 2015," 2015). This event marked a critical juncture in the acceptance of agroecology as a viable alternative to industrial agriculture, particularly following the endorsement by the FAO in 2014, which recognized it as a sustainable approach to food systems (FAO, 2014). The temporal scope of this study ensures that it encompasses the most current theoretical advancements and empirical findings pertinent to contemporary discussions on policy and practice, while also reflecting the significant evolution of feminist and agroecological thought over the past two decades. Conference papers have been excluded from this analysis, as peer-reviewed journal articles typically undergo a more rigorous quality control process. While it is recognized that innovative ideas often emerge first in conference proceedings, journal articles offer more comprehensive and validated analyses following the peer review and revision process (Kelly et al., 2014).

I also reviewed practitioner-based reports to capture practical insights and real-world applications not fully represented in academic literature. Non-peer-reviewed sources, such as websites, reports, and brochures, were examined for their practical relevance. Organisations' websites, such as the FAO, UN Data, and the World Bank, were reviewed to ensure the inclusion of authoritative and influential sources that contribute to global and regional agricultural policies and practices. In the analysis, I merged FPE insights with agroecological practices to examine power dynamics, resource distribution, women's roles and representation in agriculture, and the impact of agroecology on social equity and ecological sustainability. By synthesizing the literature, I provide an overview of current knowledge at the intersection of FPE and agroecology. The key themes identified include gendered access to resources, women's contributions to biodiversity, and the effects of equitable practices on food security. These themes will be discussed in subsequent sections.

Research Process

The research process followed four key sub-steps to ensure a rigorous and transparent approach:

(1) *Search*: A comprehensive search of the selected databases using the identified keywords and filters (post-2000 publications, peer-reviewed sources) which ensures that the research covers a wide spectrum of existing knowledge and does not overlook relevant sources. The outcome of this step is a curated compilation of research articles and studies that serve as the primary materials for the subsequent stages of the research. A successful search phase yields a dataset of relevant and contemporary literature for critical review.

(2) *Filtering*: To refine the list of collected studies, I applied inclusion/exclusion criteria, prioritizing articles that examined the intersections of gender, agroecology, and social justice. Studies irrelevant to the geographic or thematic scope (e.g., those not addressing gender or not relevant to Sub-Saharan Africa) were excluded from consideration. This selective approach facilitates the establishment of a more concentrated and manageable body of literature, thereby ensuring that the subsequent analysis is firmly grounded in the relevant contexts and aligned with the objectives of the study.

(3) *Preparation*: I categorized and organized the filtered studies according to relevant themes including gendered resource access, the role of women in agroecological practices, and sustainable food systems. This thematic organization facilitates a systematic comparison and contrast of insights drawn from various studies enabling the researcher to more readily identify patterns, trends, and gaps within literature. This structured methodology enhances the analytical process, thereby simplifying the extraction of meaningful insights and the identification of interconnections across the studies.

(4) *Analysis*: I employed a narrative synthesis approach to identify key themes and debates pertinent to the integration of FPE and agroecology, the implications for social equity, and the influence of gender in the transformation of food systems. By concentrating on these themes, the analysis not only reviews existing knowledge but also provides critical evaluations and recommendations. This methodology facilitates a comprehensive synthesis of current literature, highlights gaps in existing research, and suggests avenues for future inquiry and policy interventions. The outcome is intended to yield actionable insights that advance the fields of gender studies, agroecology, and social justice, particularly in relation to their intersections within the context of Sub-Saharan Africa.

This research process is illustrated in Table 1 below which shows all the steps followed:

Table 1. Research process.

Step	Objective	Databases used	Search terms	Exclusion criteria	Outcome
Search	To gather a comprehensive collection of relevant literature on the chosen themes.	JSTOR, Web of Science, Google Scholar	Agroecology; Feminist Political Ecology; Gender Dynamics in Agriculture; Sustainable Food Systems in SSA.	Studies before 2000, non-peer-reviewed journal articles, irrelevant geographical focus.	A broad collection of academic articles, reports, and grey literature relevant to the study's focus.
Filtering	To ensure the selection of high-quality, relevant studies that align with the research questions.	JSTOR, Web of Science, Google Scholar	Agroecology, Feminist Political Ecology, Gender Dynamics in Agriculture, Sustainable Food Systems in SSA	Articles not directly addressing gender, agroecology, or Sub-Saharan African context.	A refined selection of high-quality, relevant literature for detailed review.
Preparation	To categorize and organize the articles based on common themes and relevance to the study.	Organised by key themes and relevance	Keywords related to gender and sustainability in agriculture	Articles that do not align with identified key themes or are overly generalized.	An organized repository of categorized articles to facilitate narrative synthesis.
Analysis	To critically synthesize the literature and extract key insights for the study's objectives.	Thematic synthesis of selected articles	N/A	N/A	The extraction of key themes and insights for integration into the study's findings and recommendations.

As a central argument, I emphasize the need to integrate gender perspectives into agricultural policies and practices to achieve sustainable and equitable food systems. Through an in-depth analysis of documented case studies (to access concrete, real-world empirical evidence), I demonstrate the diverse socio-ecological contexts and practical challenges of implementing agroecological practices in SSA. This approach bridges a critical gap in literature by providing empirical evidence of the benefits of integrating FPE with agroecology. It offers actionable insights for policy and practice, grounded in robust theoretical insights, for enhancing equity and sustainability in agricultural systems in SSA.

4. Transition to Agroecology as an Alternative to Industrial Agriculture

Having established the critical role of FPE in addressing gender disparities and promoting equity in agricultural practices, I now turn to agroecology as an alternative to industrial agriculture. Nikiema defines agroecology transitions as:

The set of linked technical and organizational processes by which new production modes based on agroecological principles gradually and sustainably replace systems resulting from conventional intensification that have led to the massive use of synthetic inputs or allow very low productivity farmers to intensify their production without reproducing this conventional intensification scheme (Nikiema et al., 2023, p.2).

Agroecology emphasizes ecological sustainability, social justice, and food sovereignty, offering a transformative approach to food systems that align with the FPE principles. In this section, I introduce agroecology's principles of prioritizing natural processes and community relationships, highlighting its potential to address environmental degradation, socio-economic inequalities, and gender disparities. The narrative explores agroecology's benefits for environmental sustainability, biodiversity conservation, empowering smallholder farmers, and promoting gender equality and women's empowerment in agriculture. While acknowledging critiques and challenges, I emphasize the urgent need for robust policy support and public funding to facilitate the transformative transition to agroecological practices, ultimately fostering a more just and resilient food system.

4.1 Sowing the Seeds of Harmony: The Agroecological Symphony

The fundamental principles of agroecology prioritize natural processes and community relationships over industrial inputs. Gliessman defines agroecology as:

The integration of research, education, action, and change that brings sustainability to all parts of the food system: ecological, economic, and social. It's transdisciplinary in that it values all forms of knowledge and experience in food system change. It's participating in that it requires the involvement of all stakeholders from the farm to the table and everyone in between. It is action-oriented because it confronts the economic and political power structures of the current industrial food system with alternative social structures and policy action. The approach is grounded in ecological thinking where a holistic, systems-level understanding of food system sustainability is required (Gliessman, 2018, p.599)

Moreover, agroecology approaches are based on the fact that food systems comprise science, practice, and social movement to achieve holistic integration and sustainability. It is a movement advocating for a transformative approach to food production (Rosset & Martínez-Torres, 2012). Recognized as a scientific field, agroecology explores ways to transform the existing food system, further develop agriculture toward social and ecological ends, and adapt to the changing environment (Gliessman, 2018). These multiple benefits make agroecology an essential strategy for ensuring food security.

Agroecology aims to improve land productivity by maximizing production per hectare through ecosystem synergies (Bernard & Lux, 2017). The intensification of agroecology can contribute to environmental preservation and sustainable agricultural transformation, particularly in SSA. It is not merely a collection of farming practices but a holistic approach that views the entire food system through ecological, cultural, political, social, and economic lenses. This approach promotes biodiversity, resource recycling, water conservation, and balanced energy usage while considering gender dimensions (Gliessman, 2016, 2018). Agroecology highlights the importance of local knowledge, participatory processes, and the agency of community-focused food producers over profit-motivated corporations. It embraces the rich cultural knowledge of indigenous and traditional farming communities, enabling them to control their agricultural practices and resources (Altieri et al., 2015; Pimbert, 2016).

Furthermore, agroecology emphasizes the importance of biodiversity, and ecological synergies, which are critical for the sustainability of small-scale farms (Wezel et al., 2015). It helps protect, restore, and improve agricultural systems in the face of climate shocks and stressors by promoting crop diversification, agroforestry, and organic farming. This approach not only enhances soil fertility and mitigates erosion but also supports greater carbon sequestration and increases the resilience of livelihoods, providing effective solutions for climate change mitigation and adaptation (Sachet et al., 2021). It emphasizes farmer autonomy and the use of locally sourced, renewable inputs (Gliessman, 2016), to offer a sustainable alternative to the industrial agriculture model, creating more equitable food systems that support socio-economic equity and empower marginalized communities' economic viability and environmental sustainability (Anderson et al., 2021).

4.2 Cultivating Equality: Empowering Women Through Agroecology

The discourse surrounding the impact of prioritizing gender equality in agricultural productivity is multifaceted. According to many scholars, agroecology not only transforms farming systems but also restructures social hierarchies by empowering smallholder farmers and, when women have access to resources and their knowledge and contributions are valued, by promoting gender equity in agricultural practices in SSA (Adu Boahen et al., 2024). Despite their crucial roles in food production and resource management, women in many parts of Africa face significant barriers that limit their economic opportunities and rights. Agroecological approaches are uniquely positioned to address these disparities because they emphasize inclusivity and community participation.

When guided by social justice values, agroecology aims to tackle power imbalances and inequalities by using traditional knowledge and inclusive processes that empower producers. Agroecology is found to pose a challenge to patriarchal and oppressive systems (Zaremba et al., 2021), to acknowledge and incorporate cultural aspects of farming, and preserve diverse traditions, thereby valuing women's role in agriculture and strengthening community resilience (Altieri & Nicholls, 2020). Indigenous communities, especially women within them, have preserved agroecological practices, which enhance their food sovereignty and protect their cultural heritage (Anderson et al., 2019; Shiva, 2016). Gender dynamics are at work here as agroecology promotes the use of indigenous knowledge and political economies, which often value women's role in agriculture and align with women's priorities within the sphere of social reproduction. In Malawi, women have been leaders in seed preservation and biodiversity through community seed banks, which support agroecological farming by preserving local seed varieties that are more resilient to climate change (Bizikova et al., 2022; Puskur et al., 2021). This involvement boosts agricultural biodiversity and positions women as key stakeholders in combating climate change, enhancing crop diversity supported by passed-down indigenous and traditional knowledge (Phiri et al., 2022).

Although women hold a pivotal position in food production, they frequently encounter discriminatory treatment, as well as restricted access to resources and mechanisms for decision-making (Wezel et al., 2020). Agroecology creates the social conditions for those involved in food production, and rural community members, to recognize the important role of women. It is being used by women to strengthen their capacity, seek independent financial resources, and protect their rights. By involving women and promoting gender equality, practicing AE can help women feel empowered and part of society (Serpossian et al., 2022). Hence, acknowledging the contributions of women and marginalized communities can improve social justice within food systems. Feminist perspectives in agroecology stress the need to tackle social inequalities, especially those affecting women due to patriarchal norms (Zaremba et al., 2021).

While critics argue that gender-centric policies could complicate agricultural programs and detract from their efficiency and output, a review of the literature suggests otherwise. As indicated by Kilic et al. (2015), incorporating gender equality in agriculture leads to better productivity, sustainability, and fairness. Addressing these disparities can significantly improve overall agricultural outcomes by ensuring that women, who constitute a substantial part of the agricultural workforce, have equal access to resources, inputs, and training (Perelli et al., 2024). Insights from the Nigerian agricultural promotion policy emphasize the importance of gender and age-sensitive policies in creating an enabling environment for entrepreneurship within the agricultural sector (Ifeoma, 2019). This indicates how gender-centric policies can foster a more inclusive and dynamic agricultural sector, potentially leading to innovation and growth.

Many studies, including those by Slavchevska et al. (2016); Quisumbing et al. (2019), and Haug et al. (2021), highlight that the feminization of agriculture does not always lead to women's empowerment but can instead be associated with poverty and rural distress. This challenges the assumption that increased female participation in agriculture automatically translates to improved gender equality and economic empowerment. However, Mukasa and Salami (2016) have a different view. Their research shows that gender equality not only stands as a fundamental goal but also enhances agricultural productivity, sustainability, and broader developmental objectives. For instance, closing gender gaps in agriculture in Nigeria, Tanzania, and Uganda could increase production by 2.8%, 8.1%, and 10.3%, respectively. Similarly, a 2023 report by the FAO on the Status of Women in Agrifood Systems highlights a powerful opportunity: if women farmers had equal access to resources compared to men, their agricultural output could rise by 30%, potentially reducing the number of hungry people worldwide by 12 to 17% (Solomon et al., 2024). Recognizing this potential and addressing the existing gender gap in agriculture are key aspects of agroecology, which aims to promote gender equity and women's empowerment.

Thus, agroecology serves as a tool for gender equality and empowerment by integrating feminist principles into agricultural practices (Altieri & Nicholls, 2020; Serpossian et al., 2022). It recognizes the critical role of women in food production and seeks to address gender disparities by promoting equitable access to resources, decision-making power, and economic opportunities (Shiva, 1992; Zaremba et al., 2021). To further this empowerment, development agencies, and governments should establish programs that focus on valuing women's contribution to agroecology and supporting women's participation and training in community-based agroecological initiatives. Moreover, by addressing gender disparities in agriculture and developing platforms for women to share their agroecological experiences and achievements, there is a potential to unlock the capabilities of a significant portion of the agricultural workforce. This agroecology approach orients itself towards the goals of the FPE, which advocates for policies that promote and enable gender equality in agriculture and food systems. In the next section, I will now examine how a feminist perspective in agroecology can challenge patriarchal norms, promote social justice, and restructure inequalities within food systems.

5. Empowering Change: Feminist Political Ecology in Agroecology

FPE in agroecology examines the complex relationships between gender, ecology, and agriculture, addressing the historical gender-blindness of traditional agricultural approaches. This framework explores the social, economic, and political factors that shape women's experiences in agricultural systems (Oteros-Rozas et al., 2019). Drawing on the work of scholars like Naves and Fontoura (2021) and Oteros-Rozas et al. (2019), FPE investigates key aspects of agroecological systems through a gendered lens. These aspects include equitable resource distribution, the impact of patriarchal norms on agricultural practices and decision-making, the recognition and valuation of women's agencies and local knowledge, and the role of collective action in promoting gender equality within agroecology. By integrating feminist theory, political ecology, and agroecology, I aim to show how agroecological practices have the potential to transform dominant social relations into more inclusive and resilient ones. This framework emphasizes the importance of diverse perspectives, intersectionality, local practices, food sovereignty, and environmental justice to create equitable and sustainable food systems (Teixeira et al., 2018; Zaremba et al., 2021).

A critical aspect of FPE is its focus on equitable resource distribution, which strongly influences gender power dynamics in food systems (Anderson et al., 2019). Naves and Fontoura (2021) highlight how patriarchal norms perpetuate gender inequalities in access to land, inputs, finances, and markets, limiting women's control over agricultural resources. Similarly, Anderson et al. (2019) emphasize that agroecological practices often require a labor-intensive approach, leading to changes in gender roles and responsibilities, with women taking on greater responsibilities through their work both on farms and in households. FPE demands a nuanced understanding of how agroecological practices can be reformed to become more inclusive and supportive of more equitable gender relations by focusing on the gendered allocation of resources.

The FPE approach challenges existing patriarchal structures that often sideline or ignore women's long-standing contributions to agriculture and food security. Assan et al. (2018) urges that women's agency and local knowledge of sustainability need to be acknowledged in agricultural policies. Historically, women's knowledge and labor have been pivotal in the success of sustainable farms. Women's specific knowledge and skills acquired through their work in social reproduction, gardening, and tradition are crucial to agriculture and natural resource management, yet their contributions have frequently been overlooked and marginalized (Clement et al., 2019; Mollett et al., 2020). FPE champions an agroecological approach that upholds human rights, including those of women, youth, and Indigenous peoples, and respects local cultures, social participation, and traditional food practices (Teixeira et al., 2018). This not only supports women's empowerment women but also the sustainability and resilience of agricultural systems. Implementing gender-responsive agricultural policies can amplify women's roles in sustainable farming, creating more equitable and inclusive agroecological systems.

Furthermore, the FPE promotes collective action as a tool for enhancing gender equality within agroecology. The FPE framework recognizes the benefits of gender equality, including enhanced cross-gender knowledge sharing and learning (Zaremba et al., 2021). Scholars such as Clement et al. (2019), Elmhirst (2015), and Lau (2020) have examined various forms of collective action rooted in social justice, revealing how different identities impact participation and decision-making in resource management. Women's ecological knowledge and agricultural expertise can significantly contribute to collective decision-making, thereby enriching agroecological practices and enhancing social equity and cohesion. The insistence on collectivizing resources is important as it advances the efforts by women to gain equitable access to resources and support networks that were previously out of reach on an individual basis. This can create economic opportunities, including better market access, and stronger social capital (Isgren & Ness, 2017).

It is essential to recognize that while collective action within agroecology offers potential benefits, it also presents significant challenges. Eminent scholars such as Anderson et al. (2018) and Bottazzi and Boillat (2021) note that women's participation may be impeded by power dynamics and gender inequalities within communities. Patriarchal norms and structures often restrict women's access to resources, their decision-making power, and their opportunities to assume leadership roles in agroecological initiatives. These restrictions manifest through mechanisms such as gender-based violence, cultural norms that prioritize male authority, and systemic biases that limit women's educational and economic opportunities (Ramirez-Santos et al., 2023). Therefore, it is vital to include and amplify women's voices in decision-making processes and address their specific needs (de Carvalho & Bógus, 2020). Additionally, involving men in these efforts through education and relationship-building is crucial. The women's movements have advocated such practices to foster gender equity for decades (Pichat, 2022). Intersectional factors such as race, class, and ethnicity can distinctly influence the experiences and opportunities available to women in agroecology communities (Bottazzi & Boillat, 2021; Isgren & Ness, 2017).

This disparity is highlighted in various studies exploring the dynamics of women's participation in collective action and decision-making processes across different contexts. Drawing upon the framework of FPE, I emphasize the intersectionality of social identities, women's empowerment, the importance of including diverse voices, and challenging patriarchal power structures (Zaremba et al., 2021). Evidence from Zimbabwe shows that initiatives promoting women's leadership in agroecology groups have enhanced their ability to make decisions and have their voices heard, leading to increased crop diversity and farm income (Mpofu, 2016). This benefits entire communities by bolstering food security and economic resilience. This approach enriches our understanding of collective action in agroecology by highlighting critical assumptions about shared interests and equitable outcomes. Challenges related to intersecting forms of oppression are also relevant within various governance and policymaking systems, underscoring the complexities of forming agricultural collectives.

Despite its insightful contributions, FPE faces several critiques and limitations. Sundberg (2017) argues that its perceived overemphasis on gender issues can overshadow other critical factors such as economic viability, technological advancements, and environmental challenges. However, the framework's focus on gender dynamics is vital for addressing deeply ingrained inequalities that impact agricultural productivity and sustainability. And, with intersectionality, FPE recognizes the relation between gender and other categories of social oppression. It integrates intersectional gender considerations into ecological and economic analyses, enriching our understanding of how broad social power dynamics influence access to resources like land, seeds, and credit. Lau (2020) suggests that while FPE is theoretical, it can lead to practical changes with proper policy support and community relationships, as demonstrated by initiatives promoting women's leadership in agroecology, which have enhanced crop diversity and farm income in countries like Zimbabwe (Mpofu, 2016).

Ultimately, I argue, FPE revolutionizes agroecology by integrating gender perspectives into agricultural practices. Drawing on intersectionality to embrace other critical factors alongside gender, the ongoing integration of FPE into agroecological studies enhances our understanding of gender relations in agriculture and provides actionable strategies to mitigate these challenges. While challenges exist, such as community power dynamics and patriarchal structures, case studies show that collective action and inclusive decision-making significantly benefit women and their communities. The inclusion of feminist perspectives is essential for addressing social inequalities and power disparities within agroecology. Discussions on the importance of feminist theory and activism in promoting gender equality and social justice in farming practices are crucial. Such discourses emphasize the central importance of considering gender and other social dimensions in creating fair and resilient food systems, and of acknowledging the significant contributions and experiences of women in agriculture and food systems.

Navigating Challenges and Critiques of Feminist Political Ecology in Agroecology

Agroecology, while a promising alternative to industrial agriculture, faces several critiques. A major concern is its perceived inability to produce enough food for a growing population, with some arguing that only industrial agriculture can meet global food demands (Fortuna, 2022). However, evidence suggests that the industrial system is unsustainable. With almost a century of trial and error, it has led to soil degradation, biodiversity loss, and increased greenhouse gas emissions (Capra & Lappé, 2018). Agroecology, by contrast, offers a robust alternative by utilizing diversified planting and organic methods that restore ecosystem health while still producing sufficient yields (Wezel et al., 2020).

There is also concern that "agroecology" is being co-opted by various actors to align with the dominant industrial food system, potentially depoliticizing and reshaping its discourse (Anderson et al., 2018; Anderson et al., 2021; Pimbert, 2015). Proponents worry that without maintaining its core principles, agroecology might lose its transformative potential. Therefore, transitioning to agroecological practices is urgent but complex, requiring significant upfront investment in education and infrastructure. Despite high initial costs, the long-term benefits of reduced input costs, improved soil health, and greater climate resilience provide a compelling return on investment (Fosse & Grémillet, 2020). Continued funding from governments and international bodies could facilitate the replacement of outdated and destructive farming methods.

Supportive policies are crucial for encouraging sustainable practices and providing financial incentives for small-holder farmers. For example, community-based seed systems in Tanzania preserve indigenous crop varieties and promote agro-biodiversity, helping farmers access seeds better adapted to local conditions (Ayenan et al., 2021). Such programs have increased agricultural diversity, reduced costs, and fostered greater community resilience and food security through collaborative networks among researchers, farmers, and government agencies (Kansiime et al., 2021; Sachet et al., 2021). Also, adopting agroecology within capitalist structures presents challenges and opportunities. While some argue that integrating agroecological principles into capitalist systems may not lead to desired transformations, agroecology's adaptability is crucial (Wach, 2021; Wezel et al., 2020). Effective scaling can be achieved through modern innovations and community-led agricultural planning, addressing scalability and efficiency challenges associated with traditional practices. (Ewert et al., 2023).

Gender equality in agriculture is another significant challenge. Advocating for gender equality might face cultural opposition (Zaremba et al., 2021)., particularly in African cultures where traditional roles often marginalize women, making it difficult for them to fully participate in and benefit from agricultural activities (Mukasa & Salami, 2016). These cultural and societal norms can hinder the implementation of gender equality initiatives, perpetuating gender disparities and limiting women's potential (Hernandez et al., 2023). Addressing these disparities is essential for enhancing agricultural productivity and achieving broader developmental goals (Chekene & Kashim, 2018).

Similarly, critics of FPE argue that it sometimes overemphasizes gender issues at the expense of economic viability, technological advancements, and environmental challenges (Sundberg, 2017). Moreover, integrating intersectionality into practical applications is complex and resource-intensive (Harcourt, 2020). FPE emphasizes the importance of considering gender alongside class, race, and other dimensions of political-ecological life, adding complexity to research and practical applications (Elmhirst, 2011; Rocheleau et al., 1996; Sundberg, 2017). This is highlighted by the need to integrate feminist methodologies and principles into research designs, recognize diverse epistemologies, and incorporate reflexivity, responsibility, and co-production in research. However, these participatory and inclusive research methods, while valuable, can be time-consuming and resource-intensive.

Translating FPE principles into actionable policies and practices is challenging, especially in contexts with entrenched patriarchal norms. FPE critiques dominant power structures and emphasizes the need to challenge inequality and differentiated resource access (Elias et al., 2021). The localized and context-specific nature of many FPE studies can limit the scalability, necessitating further research on applying these insights across different contexts and scales (Mollett & Faria, 2013). Addressing these critiques and challenges is crucial for the continued development and relevance of FPE, ensuring it remains a robust and influential framework for understanding and addressing complex socio-ecological issues (Rocheleau & Nirmal, 2015; Sultana, 2021). Ultimately, both agroecology and FPE revolutionize agricultural practices by integrating ecological and gender perspectives, respectively, into agricultural practices. Despite the challenges, such as community power dynamics and patriarchal structures, case studies show that collective action and inclusive decision-making significantly benefit women and their communities. Therefore, the inclusion of feminist perspectives is essential for addressing social inequalities and power disparities within agroecology.

6. Conclusion

In conclusion, this article contributes to the literature on feminism and agroecology by integrating FPE with agroecology to propose a transformative approach to addressing the intertwined challenges of sustainable and gender-equitable food systems in SSA. This proposed approach is both theoretical and practical. The theoretical framework is grounded in feminist and ecological principles, emphasizing the importance of gendered power relations, intersectionality, and equitable resource governance and distribution. On the practical side, it provides actionable recommendations, advocating for gender-responsive policies, women-led capacity building, and the integration of local ecological knowledge, including women's knowledge. This dual contribution of theoretical insights and practical steps highlights the importance of a holistic approach to achieving sustainable and gender-equitable food systems.

Through empirical evidence from case studies, I explore the real-world benefits of this integrated approach thus offering a robust framework for future research and policy development. For instance, the Green Belt Movement in Kenya, led by Wangari Maathai, involved women in tree planting to combat deforestation, promote sustainable livelihoods, and empower women politically and economically. Similarly, in Malawi, women's leadership in seed preservation through community seed banks has supported agroecological farming by preserving local seed varieties resilient to climate change. These initiatives demonstrate that embedding gender considerations into agroecological practices enhances agricultural productivity and sustainability while advancing gender equality and social justice, ultimately contributing to more resilient and equitable food systems.

FPE offers crucial insights for addressing potential risks and problems that may arise when implementing agroecology without a feminist approach. It challenges existing patriarchal structures, promotes collective action, and emphasizes the importance of women's voices in decision-making processes to ensure that agroecological practices do not inadvertently perpetuate or exacerbate gender inequalities. Furthermore, FPE's recognition of intersectionality and its focus on equitable resource distribution contributes to a more nuanced understanding of the complex social dynamics within agroecological communities.

Building on these foundational insights, emerging directions and future research agendas in FPE emphasize greater intersectional approaches that examine how gender intersects with other axes of difference such as race, class, and sexuality across multiple scales. Future research should aim to develop more integrated methodologies that balance gender analysis with other critical factors, explore ways to scale up and generalize FPE insights for broader policy application, and strengthen connections between FPE theory and practical implementation. Amplifying diverse voices within FPE, particularly from the Global South, and critically examining the intersection of gender, environment, and emerging technologies are also crucial. FPE scholars increasingly focus on the gendered implications of digital technologies and climate justice, advocating for more equitable and sustainable futures. By engaging in these debates and limitations, the FPE can continue evolving as a robust and influential framework for understanding and addressing complex socio-ecological issues. Pursuing these emerging directions will ensure that FPE continues to offer critical insights into the gendered dimensions of environmental change, enhancing the sustainability and equity of food systems globally.

CRediT Author Statement: This is a single author paper, and the author was solely responsible for the content, including the concept, design, analysis, writing, and revision of the manuscript.

Data Availability Statement: Not applicable.

Funding: This research was funded by FORMAS, a Swedish research council for sustainable development, under Grant number 2020-00397.

Conflicts of Interest: The author declares no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgments: Not applicable.

References

Adu Boahen, E., Boateng Dankwah, J., & Berko, D. (2024). Understanding the gender gap in productivity in agricultural production among smallholder cereal growers in rural Ghana. *Cogent Economics & Finance*, *12*(1), 2318979. https://doi.org/10.1080/23322039.2024.2318979

Ajibade, S., Simon, B., Gulyas, M., & Balint, C. (2023). Sustainable intensification of agriculture as a tool to promote food security: A bibliometric analysis. *Frontiers in Sustainable Food Systems*, *7*. https://doi.org/10.3389/fsufs.2023.1101528

Altieri, M. A., & Nicholls, C. I. (2020). Agroecology: Challenges and opportunities for farming in the Anthropocene. *International Journal of Agriculture and Natural Resources*, *47*(3), 204–215. https://doi.org/10.7764/ijanr.v47i3.2281

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, *35*, 869–890. https://doi.org/10.1007/s13593-015-0285-2

Amede, T., Konde, A. A., Muhinda, J. J., & Bigirwa, G. (2023). Sustainable farming in practice: Building resilient and profitable smallholder agricultural systems in Sub-Saharan Africa. *Sustainability*, *15*(7), 5731. https://doi.org/10.3390/su15075731

Anderson, C. R., Maughan, C., & Pimbert, M. P. (2018). Transformative agroecology learning in Europe: Building consciousness, skills and collective capacity for food sovereignty [Special issue]. *Agriculture and Human Values, 36*. https://doi.org/10.1007/s10460-018-9894-0

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., & Pimbert, M. P. (2019). From transition to domains of transformation: Getting to sustainable and just food systems through agroecology. *Sustainability*, *11*(19), 5272. https://doi.org/10.3390/su11195272

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., & Pimbert, M. P. (2021). Power, governance and agroecology transformations. In *Agroecology now!: Transformations towards more just and sustainable food systems* (pp. 153–173). Palgrave Macmillan Cham. https://doi.org/10.1007/978-3-030-61315-0_10

Assan, E., Suvedi, M., Olabisi, L. S., & Allen, A. (2018). Coping with and adapting to climate change: A gender perspective from smallholder farming in Ghana. *Environments*, *5*(8), 86. https://doi.org/10.3390/environments5080086

Ayenan, M. A. T., Aglinglo, L. A., Zohoungbogbo, H. P. F., N'Danikou, S., Honfoga, J., Dinssa, F. F., Hanson, P., & Afari-Sefa, V. (2021). Seed systems of traditional African vegetables in Eastern Africa: A systematic review. *Frontiers in Sustainable Food Systems*, *5*. https://doi.org/10.3389/fsufs.2021.689909

Bernard, B., & Lux, A. (2017). How to feed the world sustainably: An overview of the discourse on agroecology and sustainable intensification. *Regional Environmental Change*, *17*, 1279–1290. https://doi.org/10.1007/s10113-016-1027-y

Bizikova, L., de Brauw, A., Rose, M. E., Laborde, D., Motsumi, K., Murphy, M., Parent, M., Picard, F., & Smaller, C. (2022). *Achieving sustainable food systems in a global crisis: Malawi*. International Institute for Sustainable Development. https://www.iisd.org/publications/report/sustainable-food-systems-global-crisis-malawi

Bottazzi, P., & Boillat, S. (2021). Political agroecology in Senegal: Historicity and repertoires of collective actions of an emerging social movement. *Sustainability*, *13*(11), 6352. https://doi.org/10.3390/su13116352

Bryan, E., Alvi, M., Huyer, S., & Ringler, C. (2024). Addressing gender inequalities and strengthening women's agency to create more climate-resilient and sustainable food systems. *Global Food Security, 40*, 100731. https://doi.org/10.1016/j.gfs.2023.100731

Capra, F., & Lappé, A. (2018). Is agroecology the antidote to industrial agriculture? In *Understanding food and climate change: A systems perspective*. Center for Ecoliteracy. https://foodandclimate.ecoliteracy.org/systems-perspective/pg0013.xhtml

Chekene, M. B., Kashim, I. U. (2018). Gender equality: Women in agriculture or gender in agriculture. *Agricultural Research & Technology, 18*(5), 239–242. https://doi.org/10.19080/ARTOAJ.2018.18.556074

Cho, S., Crenshaw, K. W., & McCall, L. (2013, summer). Toward a field of intersectionality studies: Theory, applications, and praxis. *Signs: Journal of Women in Culture and Society, 38*(4), 785–810. https://doi.org/10.1086/669608

Clement, F., Harcourt, W. J., Joshi, D., & Sato, C. (2019). Feminist political ecologies of the commons and commoning. *International Journal of the Commons, 13*(1), 1–15. https://doi.org/10.18352/ijc.972

de Carvalho, L. M., & Bógus, C. M. (2020). Gender and social justice in urban agriculture: The network of agroecological and peripheral female urban farmers from São Paulo. *Social Sciences*, *9*(8), 127. https://doi.org/10.3390/socsci9080127

Declaration of the International Forum for Agroecology, Nyéléni, Mali: 27 February 2015. (2015). *Development*, *58*(2–3), 163–168. https://doi.org/10.1057/s41301-016-0014-4

Elias, M., Joshi, D., & Meinzen-Dick, R. (2021). Restoration for whom, by whom? A feminist political ecology of restoration. *Ecological Restoration*, *39*(1–2), 3–15. https://doi.org/10.3368/er.39.1-2.3

Elmhirst, R. (2011). Introducing new feminist political ecologies. *Geoforum, 42*(2), 129–132. https://doi.org/10.1016/j.geoforum.2011.01.006

Elmhirst, R. (2015). Feminist political ecology. In T. Perreault, G. Bridge, J. McCarthy (Eds.), *The Routledge handbook of gender and development* (pp. 519–530). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315759289-48/feminist-political-ecology-rebecca-elmhirst

Elmhirst, R. (2017). Ecologías políticas feministas: perspectivas situadas y abordajes emergentes [Feminist political ecologies: Situated perspectives, emerging engagements]. *Ecologia Politica*, (54), 52–59. https://www.ecologiapolitica.info/wp-content/uploads/2018/01/054_Elmhirst_2017.pdf

Ewert, F., Baatz, R., & Finger, R. (2023). Agroecology for a sustainable agriculture and food system: From local solutions to large-scale adoption. *Annual Review of Resource Economics, 15*, 351–381. https://doi.org/10.1146/annurev-resource-102422-090105

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., … Zaks, D. P. M. (2011). Solutions for a Cultivated Planet. *Nature*, *478*(7369), 337–342. https://doi.org/10.1038/nature10452

Food and Agriculture Organization of the United Nations. (2011). Women in agriculture: closing the gender gap for development. In The state of food and agriculture (pp.1–63). https://www.fao.org/4/i2050e/i2050e.pdf

Food and Agriculture Organization of the United Nations. (2014). *Building a Common Vision for Sustainable Food and Agriculture: Principles and approaches*. http://www.fao.org/3/a-i3940e.pdf

Food and Agriculture Organization of the United Nations. (2023). *The status of women in agrifood systems*. https://openknowledge.fao.org/handle/20.500.14283/cc5343en

Forsyth, T. (2004). *Critical political ecology: The politics of environmental science* (1st ed.). Routledge. https://doi.org/10.4324/9780203017562

Fortuna, C. (2022). *Industrial agricultural needs to be replaced by agroecology — Soon.* CleanTechnica. https://cleantechnica.com/2022/10/31/industrial-agricultural-needs-to-be-replaced-by-agroecology-soon/

Fosse, J., & Grémillet, A. (2020). *The economic and environmental performance of agroecology*. France Strategie. https://www.strategie.gouv.fr/english-articles/economic-and-environmental-performance-agroecology

Gliessman, S. (2016). Transforming food systems with agroecology. *Agroecology and Sustainable Food Systems*, *40*(3), 187–189. https://doi.org/10.1080/21683565.2015.1130765

Gliessman, S. (2018). Defining agroecology. *Agroecology and Sustainable Food Systems*, *42*(6), 599–600. https://doi.org/10.1080/21683565.2018.1432329

Gusenbauer, M., & Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. *Research Synthesis Methods*, *11*(2), 181–217. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7079055/pdf/JRSM-11-181.pdf

Harcourt, W. (2020). Reflections from a feminist political ecology perspective. In J. Clancy, G. Özerol, N. Mohlakoana, M. Feenstra, & L. Sol Cueva (Eds.), *Engendering the energy transition* (pp. 275–278). Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-43513-4_19

Harcourt, W., Agostino, A., Elmhirst, R., Gómez, M., & Kotsila, P. (Eds.). (2023). *Contours of feminist political ecology.* Palgrave Macmillan Cham. https://doi.org/10.1007/978-3-031-20928-4

Haug, R., Mwaseba, D. L., Njarui, D., Moeletsi, M., Magalasi, M., Mutimura, M., Hundessa, F., & Aamodt, J. T. (2021). Feminization of African agriculture and the meaning of decision-making for empowerment and sustainability. *Sustainability, 13*(16), 8993. https://doi.org/10.3390/su13168993

Hernandez, M. A., Alarcon, C., Berrospi, M. L., Lopera, D., Quintero, D., Reyes, B., & Olivet, F. (2023). Cultural and economic barriers and opportunities for the participation of women in agricultural production systems: A case study in Guatemala. *Frontiers in Sustainable Food Systems*, 7. https://doi.org/10.3389/fsufs.2023.1185756

Hunt, K. P. (2014). "It's more than planting trees, it's planting ideas": Ecofeminist praxis in the Green Belt Movement. *Southern Communication Journal*, *79*(3), 235–249. https://doi.org/10.1080/1041794X.2014.890245

Ifeoma, O. D. (2019). A review of the Nigerian agricultural promotion policy (2016–2020): Implications for entrepreneurship in the agribusiness sector. *International Journal of Agricultural Policy and Research*, *7*(3), 70–79. https://doi.org/10.15739/IJAPR.19.008

Isgren, E., & Ness, B. (2017). Agroecology to promote just sustainability transitions: Analysis of a civil society network in the Rwenzori Region, Western Uganda. *Sustainability*, *9*(8), 1357. https://doi.org/10.3390/su9081357

Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmore, R., Aggarwal, P., Bhatta, G., Chaudhury, M., Tapio-Biström, M.-L., Nelson, S., & Kristjanson, P. (2015). Understanding gender dimensions of agriculture and climate change in smallholder farming communities. *Climate and Development*, *8*(2), 133–144. https://doi.org/10.1080/17565529.2015.1050978

Kansanga, M. M., Antabe, R., Sano, Y., Mason-Renton, S., & Luginaah, I. (2019). A feminist political ecology of agricultural mechanisation and evolving gendered on-farm labour dynamics in Northern Ghana. *Gender, Technology and Development*, *23*(3), 207–233. https://doi.org/10.1080/09718524.2019.1687799

Kansiime, M. K., Bundi, M., Nicodemus, J., Ochieng, J., Marandu, D., Njau, S. S., Kessy, R. F., Williams, F., Karanja, D., Tambo, J. A., & Romney, D. (2021). Assessing sustainability factors of farmer seed production: A case of the Good Seed Initiative project in Tanzania. *Agriculture & Food Security*, *10*, 15. https://doi.org/10.1186/s40066-021-00289-7

Kelly, J., Sadeghieh, T., & Adeli, K. (2014). Peer review in scientific publications: Benefits, critiques, & a survival guide. *Ejifcc*, *25*(3), 227–243. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4975196/pdf/ejifcc-25-227.pdf

Kilic, T., Palacios-Lopez, A., & Goldstein, M. (2015). Caught in a productivity trap: A distributional perspective on gender differences in Malawian Agriculture. *World Development*, *70*, 416–463. https://doi.org/10.1016/j.worlddev.2014.06.017

Lau, J. D. (2020). Three lessons for gender equity in biodiversity conservation. *Conservation Biology*, *34*(6), 1589–1591. https://doi.org/10.1111/cobi.13487

Lawhon, M., Ernstson, H., & Silver, J. (2013). Provincializing urban political ecology: Towards a situated UPE through African Urbanism. *Antipode*, *46*(2), 497–516. https://doi.org/10.1111/anti.12051

Manji, A. (2020). *The struggle for land and justice in Kenya*. Boydell & Brewer.

Mohanty, C. T. (2003, winter). "Under Western Eyes" revisited: Feminist solidarity through anticapitalist struggles. *Signs: Journal of Women in Culture and Society*, *28*(2), 499–535. https://doi.org/10.1086/342914

Mollett, S. (2017). Gender's critical edge: Feminist political ecology, postcolonial intersectionality, and the coupling of race and gender. In S. MacGregor (Ed.), *Routledge handbook of gender and environment* (pp. 146–158). Routledge. https://doi.org/10.4324/9781315886572

Mollett, S., & Faria, C. (2013). Messing with gender in feminist political ecology. *Geoforum*, *45*, 116–125. https://doi.org/10.1016/j.geoforum.2012.10.009

Mollett, S., Vaz-Jones, L., & Delicado-Moratalla, L. (2020). Feminist political ecologies: Race, bodies and the human. In A. Datta, P. Hopkins, L. Johnston, E. Olson, & J. M. Silva (Eds.), *Routledge handbook of gender and feminist geographies* (pp. 271–284). Routledge. https://doi.org/10.4324/9781315164748
Mpofu, E. (2016, September 20). *Opinion: Agroecology for gender equality*. La Via Campesina. https://viacampesina.org/en/opinion-agroecology-for-gender-equality/
Mukasa, A. N., & Salami, A. O. (2016). Gender equality in agriculture: What are really the benefits for sub-Saharan Africa? *Africa Economic Brief*, *7*(3). https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/AEB_Vol_7_Issue_3_Gender_equality_in_agriculture.pdf
Naves, F., & Fontoura, Y. (2021). Feminist resistance building in the Brazilian agroecology movement: A gender decoloniality study. *Gender Work and Organization*, *29*(2), 408–426. https://doi.org/10.1111/gwao.12767
Nightingale, A. (2006). The nature of gender: Work, gender, and environment. *Environment and Planning D: Society and Space, 24*(2), 165–185. https://doi.org/10.1068/d01k
Nikiema, T., Ezin, E. C., & Kpenavoun Chogou, S. (2023). Bibliometric analysis of the state of research on agroecology adoption and methods used for its assessment. *Sustainability*, *15*(21), 15616. https://doi.org/10.3390/su152115616
Oteros-Rozas, E., Ravera, F., & García-Llorente, M. (2019). How does agroecology contribute to the transitions towards social-ecological sustainability? *Sustainability*, *11*(16), 4372. https://doi.org/10.3390/su11164372
Perelli, C., Cacchiarelli, L., Peveri, V., & Branca, G. (2024). Gender equality and sustainable development: A cross-country study on women's contribution to the adoption of the climate-smart agriculture in Sub-Saharan Africa. *Ecological Economics*, *219*, 108145. https://doi.org/10.1016/j.ecolecon.2024.108145
Phiri, A. T., Charimbu, M., Edewor, S. E., & Gaveta, E. (2022). Sustainable scaling of climate-smart agricultural technologies and practices in Sub-Saharan Africa: The case of Kenya, Malawi, and Nigeria. *Sustainability*, *14*(22), 14709. https://doi.org/10.3390/su142214709
Pichat, S. K. (2022, November 28). *The role of men in achieving gender equality*. United Nations Development Programme. https://www.undp.org/bosnia-herzegovina/blog/role-men-achieving-gender-equality
Pimbert, M. (2015). Agroecology as an alternative vision to conventional development and Climate-smart Agriculture. *Development*, *58*, 286–298. https://doi.org/10.1057/s41301-016-0013-5
Pimbert, M. (2016). Constructing knowledge for food sovereignty, agroecology and biocultural diversity. In M. Pimbert (Ed.), *Food sovereignty, agroecology and biocultural diversity* (pp. 1–56). Taylor & Francis. https://library.oapen.org/handle/20.500.12657/40147
Puskur, R., Mudege, N. N., Njuguna-Mungai, E., Nchanji, E., Vernooy, R., Galiè, A., & Najjar, D. (2021). Moving beyond reaching women in seed systems development. In R. Pyburn, A. van Eerdewijk (Eds.), *Advancing gender equality through agricultural and environmental research: Past, present and future* (pp. 113–145). International Food Policy Research Institute. https://doi.org/10.2499/9780896293915
Quisumbing, A. R., Meinzen-Dick, R. S., & Njuki, J. (2019). *2019 Annual trends and outlook report: Gender equality in rural Africa: From commitments to outcomes*. International Food Policy Research Institute. https://doi.org/10.2499/9780896293649
Ramirez-Santos, A. G., Ravera, F., Rivera-Ferre, M. G., & Calvet-Nogués, M. (2023). Gendered traditional agroecological knowledge in agri-food systems: A systematic review. *Journal of Ethnobiology and Ethnomedicine*, *19*, 11. https://doi.org/10.1186/s13002-023-00576-6
Rocheleau, D. E. (2008). Political ecology in the key of policy: From chains of explanation to webs of relation. *Geoforum, 39*(2), 716–727. https://doi.org/10.1016/j.geoforum.2007.02.005
Rocheleau, D., & Nirmal, P. (2015). Feminist political ecologies: Grounded, networked and rooted on earth. In R. Baksh, & W. Harcourt (Eds.), *The Oxford Handbook of Transnational Feminist Movements* (pp. 793–814). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199943494.013.032
Rocheleau, D., Thomas-Slayter, B., & Wangari, E. (1996). *Feminist political ecology: Global issues and local experience* (1 st ed.). Routledge. https://doi.org/10.4324/9780203352205
Rocheleau, D., Thomas-Slayter, B., & Wangari, E. (2016). Gender and environment: A feminist political ecology perspective. In N. Haenn, A. Harnish, & R. Wilk (Eds.), *The Environment in Anthropology* (2nd ed., pp. 30–40). New York University Press. https://doi.org/10.18574/nyu/9781479862689.003.0008
Rosset, P. M., & Martínez-Torres, M. E. (2012). Rural social movements and agroecology: Context, theory, and process. *Ecology and Society*, *17*(3). http://dx.doi.org/10.5751/ES-05000-170317
Sachet, E., Mertz, O., Coq, J.-F. L., Cruz-García, G. S., Francesconi, W., Bonin, M., & Quintero, M. (2021). Agroecological transitions: A systematic review of research approaches and prospects for participatory action methods. *Frontiers in Sustainable Food Systems*, 5. https://doi.org/10.3389/fsufs.2021.709401
Santpoort, R., Steel, G., Mkandawire, A., Ntauazi, C., Faye, E. H., & Githuku, F. (2021). The land is ours: Bottom-up strategies to secure rural women's access, control and rights to land in Kenya, Mozambique, Senegal and Malawi. *Frontiers in Sustainable Food Systems*, *5*. https://doi.org/10.3389/fsufs.2021.697314
Sato, C., & Alarcón, J. M. S. (2019). Toward a postcapitalist feminist political ecology approach to the commons and commoning. *International Journal of the Commons*, *13*(1), 36–61. https://doi.org/10.18352/ijc.933
Serpossian, E., Coquil, X., & Annes, A. (2022). Involvement of women farmers in the agroecological transition and transformation of their work: Chronicle of the agricultural organisation groupe femmes 44. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.869533
Shiva, V. (1992). Women's indigenous knowledge and biodiversity conservation. *India International Centre Quarterly*, *19*(1/2), 205–214. http://www.jstor.org/stable/23002230
Shiva, V. (2016). *Seed sovereignty, food security: Women in the vanguard of the fight against GMOs and corporate agriculture*. North Atlantic Books.
Slavchevska, V., Kaaria, S., & Taivalmaa, S.-L. (2016). *Feminisation of agriculture in the context of rural transformations: What is the evidence?* World Bank Group. https://doi.org/10.1596/25099
Solomon, D., Porciello, J.-A., & Savilaakso, S. (2024). *Understanding the impact of sustainable agricultural interventions on women's economic and social well-being, empowerment and gender equity*. AgriRxiv. https://doi.org/10.31220/agriRxiv.2024.00236
Sukhera, J. (2022). Narrative reviews: Flexible, rigorous, and practical. *Journal of Graduate Medical Education*, *14*(4), 414–417. https://doi.org/10.4300/jgme-d-22-00480.1

Sultana, F. (2021). Political ecology 1: From margins to center. *Progress in Human Geography*, *45*(1), 156–165. https://doi.org/10.1177/0309132520936751

Sundberg, J. (2017). Feminist political ecology. *International Encyclopedia of Geography: People, the Earth, Environment and Technology*. https://doi.org/10.1002/9781118786352.wbieg0804

Susial-Martin, P. (2017). *Apuntes para una AgroEcología Política Feminista del siglo XXI* [Towards a Feminist Political Agroecology of the 21st Century]. El Colegio de la Frontera Sur (ECOSUR). https://doi.org/10.13140/RG.2.2.15037.36326

Tavenner, K., Crane, T. A., Bullock, R., & Galiè, A. (2022). Intersectionality in gender and agriculture: Toward an applied research design. *Gender, Technology and Development*, *26*(3), 385–403. https://doi.org/10.1080/09718524.2022.2140383

Teixeira, H. M., Van dan Berg, L., Cardoso, I. M., Vermue, A. J., Bianchi, F. J. J. A., Peña-Claros, M., & Tittonell, P. (2018). Understanding farm diversity to promote agroecological transitions. *Sustainability*, *10*(12), 4337. https://doi.org/10.3390/su10124337

Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., & Batáry, P. (2021). Beyond organic farming – Harnessing biodiversity-friendly landscapes. *Trends in Ecology & Evolution*, *36*(10), 919–930. https://doi.org/10.1016/j.tree.2021.06.010

Wach, E. (2021). Market dependency as prohibitive of agroecology and food sovereignty—A case study of the agrarian transition in the Scottish Highlands. *Sustainability*, *13*(4), 1927. https://doi.org/10.3390/su13041927

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*. https://doi.org/10.1007/s13593-020-00646-z

Wezel, A., Soboksa, G., McClelland, S., Delespesse, F., & Boissau, A. (2015). The blurred boundaries of ecological, sustainable, and roecological intensification: A review. *Agronomy for Sustainable Development*, *35*, 1283–1295. https://doi.org/10.1007/s13593-015-0333-y

Wiebe, N. (2023). Shaping our collective futures: Activism, analysis, solidarity. *The Journal of Peasant Studies*, *50*(2), 627–639. https://doi.org/10.1080/03066150.2022.2163628

Zaremba, H., Elias, M., Rietveld, A., & Bergamini, N. (2021). Toward a feminist agroecology. *Sustainability*, *13*(20), 11244. https://doi.org/10.3390/su132011244

Zimmerer, K. S. (2006). Cultural ecology: At the interface with political ecology – the new geographies of environmental conservation and globalization. *Progress in Human Geography*, *30*(1), 63–78. https://doi.org/10.1191/0309132506ph591pr

Agricultural & Rural Studies

Article

Does the Different Recipients of Land Fertility Protection Subsidy Influence the Scale and Efficiency of Village Land Circulation? Evidence from a Chinese Agricultural City

Zehao Qiao [1], Maojun Wang [1,*], Tao Liu [2] and Guangzhong Cao [2]

1 School of Resources Environment & Tourism, Capital Normal University, Beijing 10048, China; zehaoqiao@188.com
2 College of Urban and Environmental Sciences, Peking University, Beijing 100871, China; liutao@pku.edu.cn (T.L.); caogzh@pku.edu.cn (G.C.)
* Correspondence: maojunw@yeah.net

Abstract: Agricultural subsidies offer significant support for the stability of global food security. With the backdrop of land circulation, the object of China's land fertility protection subsidy is becoming increasingly ambiguous. Thus, outflower and inflower sense this subsidy as a profitable opportunity. Existing research has treated all agricultural subsidies as a whole, disregarding the distinct policy goals of different agricultural subsidies. The current study subdivides agricultural subsidies, with a focus on land fertility protection subsidies, which explores the relationship between village types dominated by subsidy recipients and the scale of land circulation. The current study, conducted on the village level, reflects individual farmers' decisions influenced by such causes as village social structure and economic network. This study shows that in subsidized outflower-led villages, the scale of land circulation is considerably large, and the proportion of farmers exiting land to promote circulation is also markedly high. The land fertility protection subsidy often deviates from its intended policy goals. Furthermore, the impact of this distribution on land circulation varies among different entities in land transactions in different villages. Therefore, additional targeted and refined policy reforms are necessary to realize the original goal and effectively promote land fertility protection subsidies.

Keywords: land fertility protection subsidy; cultivated land circulation; precise subsidy system; policy reform; China

Citation: Qiao, Z., Wang, M., Liu, T., & Cao, G. (2025). Does the Different Recipients of Land Fertility Protection Subsidy Influence the Scale and Efficiency of Village Land Circulation? Evidence from a Chinese Agricultural City. *Agricultural & Rural Studies*, *3*(1), 15. https://doi.org/10.59978/03010002

Received: 21 November 2024
Revised: 13 December 2024
Accepted: 16 January 2025
Published: 24 February 2025

1. Introduction

China established a subsidy system in 2006 as part of an effort to increase fiscal support for agriculture (Veeck & Shui, 2011). However, as agricultural profitability declines and farmland fragmentation intensifies, the "generalized system of preferences" (GSP) subsidy model has struggled to address rising production costs effectively (Andrews, 2021; Sun & Lv, 2012). To address these challenges, the strategy of land circulation was introduced, aiming to consolidate cultivated land resources for scaled-up agricultural operations. Data from the Ministry of Agriculture and Rural Affairs of China indicate that since 2016, the proportion of family-contracted cultivated land circulated has remained approximately 35% of the total contracted farmland.

In the same year, the government restructured its subsidy framework, integrating direct grain subsidy, high-quality seed subsidy, and 80% of agricultural input subsidy into a unified "agricultural support and protection subsidy." This reform introduced two new categories: moderate-scale operation subsidy and land fertility protection subsidy. The land fertility protection subsidy is aimed at farmers who have land contract management rights and encourages them to actively improve soil fertility. However, the separation of farmland contracting and management rights due to land circulation has complicated the identification and allocation of subsidy beneficiaries (Guo et al., 2021).

Regional variations further complicate the implementation process (Figure 1). In such regions as Shandong and Tianjin, the primary beneficiaries of subsidy in the village are mainly actual grain growers, including traditional farmers and farmers who have entered agriculture through land circulation. By contrast, such provinces as Hebei and Henan only provide this subsidy to farmers who simultaneously hold contractual rights and actual cultivation. As the rural labor force transitions to non-agricultural sectors, this trend presents new challenges in implementing land circulation strategies.

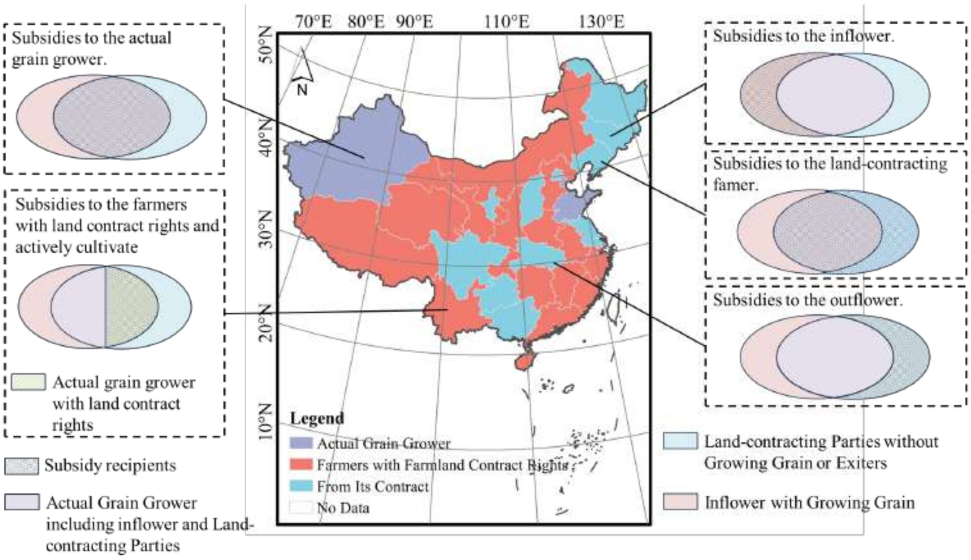


Figure 1. Provincial Policies on Recipients of Land Fertility Protection Subsidy in China.

Most regions customarily require the parties involved to sign a contract outlining the recipients of the land fertility protection subsidy. However, the specific terms and conditions of these contracts can vary depending on the region. For example, in such regions as Liaoning, Sichuan, and Guizhou, the subsidy is primarily allocated to parties who have contracted the land, regardless of their direct involvement in farming activities. These villages are subsidized outflower (SO)-led villages. In Jilin Province, the actual cultivators are legally required to receive this subsidy, and these villages are subsidized inflower (SI)-led villages. However, field interviews have revealed that this case is not always true. Furthermore, frequent changes in the main actual cultivators, driven by various interests, further complicate the distribution of this subsidy. In Hubei Province, this subsidy is distributed to outflowers when there is land circulation among farmers. However, inflow entities include farmers, village collectives, and individuals or organizations from outside the village. This situation raises the question of how the village should distribute this subsidy. These complex interest structures highlight the uncertainties in the implementation of subsidy policies.

Thus, the impact of agricultural subsidies on land circulation has long been a topic of interest in academic circles. Agricultural subsidies have been found to encourage labor contributions to agriculture (Yu & Jensen, 2010), and significantly increase agricultural production efficiency (Qian & Hong, 2016; Qi & Yang, 2022). As land circulation accelerated after the implementation of the reform, the agricultural support and protection subsidies successfully reduced the disparity in willingness to pay between individuals who engage in and discontinue the cultivation of land. Consequently, this outcome promoted the inflow of traditional farmers or new agricultural entities into land (Zhang et al., 2019; Xu et al., 2020) These findings suggest that directing subsidies to actual cultivators could encourage substantial farmer involvement in land circulation activities (Ji et al., 2015), particularly enhancing the willingness of farmers who balance between agricultural and non-agricultural incomes to adopt circulated land (Liu & Liu, 2016). During this time, the village distributed all subsidies to the actual farmers in accordance with regulations. Given that the scale of land circulation is small, the issue of subsidy distribution is also minimal. Thus, promoting land circulation (Fan et al., 2023).

However, some studies have suggested that agricultural subsidies have reduced farmers' willingness to engage in land circulation (Liao, 2012; Tian et al., 2021), thereby hindering land circulation processes (Lin & Huang, 2021). A significant portion of the existing literature has failed to distinguish between land fertility protection subsidies and moderate-scale operation subsidies. This lack of differentiation obscures the distinct policy objectives and incentive mechanisms underlying these subsidies. Specifically, the former focuses on soil quality preservation and sustainability, whereas the latter prioritizes the economic benefits of scaled agricultural operations. As a result, the absence of a clear distinction between these two subsidy types has led to conflicting conclusions regarding their respective impacts on land circulation. Furthermore, the majority of the related studies have focused on the influence of agricultural subsidies on farmers' willingness and behavior toward land circulation. However, intention does not necessarily translate into behavior. The potential impact of village characteristics on land circulation activities has often been overlooked. Farmers' decisions can vary among different villages.

Therefore, the primary inquiry is as follows: How do village types dominated by recipients of land fertility protection subsidies impact land circulation within the villages? By examining the effects of dominant subsidy recipients of dominant villages on cultivated land circulation, this research offers several contributions. First, the impact of land fertility protection subsidy on land circulation remains uncertain, as provincial regulations vary and may not align with higher-level policies. Second, the role of this subsidy as an additional income source during land circulation has been underexplored. Finally, studying this issue in China fills a critical research gap in developing countries and offers valuable insights for nations implementing similar policies.

The remainder of this paper is organized as follows. Section 2 presents the conceptual framework and theoretical hypotheses. Section 3 describes the data sources and research methodology. Section 4 conducts a regression analysis. Section 5 summarizes and discusses the research findings.

2. Theoretical Analysis and Research Hypotheses

2.1. Decision-Making Entities and Driving Mechanisms

In the context of land circulation, the decision-making actors include farmers who outflow and inflow land. Guided by the rational economic actor model, individuals involved are primarily driven by the pursuit of profit maximization (Wang et al., 2021). Consequently, the dynamics observed in different types of dominant villages and the influence of land cultivation actors on land circulation can be seen as the allocation of land resources to optimize benefits while considering various constraints (Figure 2).

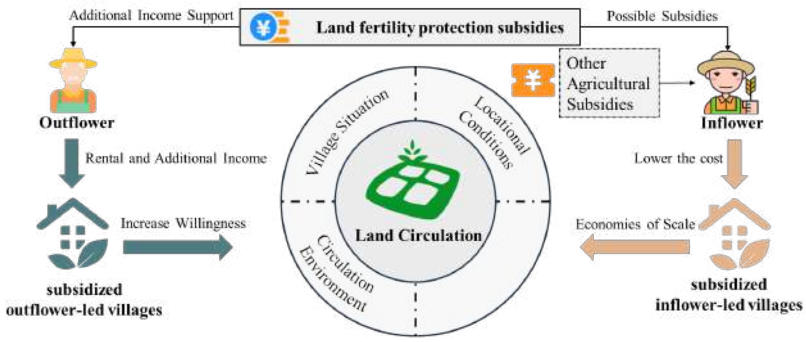


Figure 2. Theoretical framework.

Assuming the consistency of the land fertility and crop yields before and after land circulation, research has suggested that land fertility protection subsidies do not have an impact on land rental prices (Yi & McCarl, 2018; Song et al., 2022). We follow Ellis' framework on agricultural economics (Ellis, 1988/2006) and introduce Eq. (1):

$$R_i = P_i - C_i, \quad (1)$$

Here, R_i represents the net income for the entity, where i is categorized as self-cultivators, outflower, and inflower; P_i represents the total income obtained from the land; and C_i includes total costs, including agricultural inputs, labor, transaction costs, and land rent.

The extent and viability of land circulation depend on the comparative net revenues of outflowers and inflowers relative to self-cultivators.

2.2. Impacts of Subsidy on Land Circulation Behavior

Land circulation in villages primarily operates through two distinct mechanisms: interpersonal network reciprocity and market-based transactions (Ayala-Cantu & Morando, 2020; Fang, 2024). Reciprocal exchanges often involve nominal or negligible rents, particularly among close relatives or community members (Wang et al., 2018). Conversely, market-based mechanisms tend to exhibit higher transaction costs, influencing participants' sensitivity to this subsidy.

The distribution of land fertility protection subsidy without considering actual soil conservation measures, has gradually evolved into a quasi-income subsidy (Huang et al., 2011; Guo et al., 2021). In this situation, land fertility protection subsidies are considered a fixed income and is included in the net income (R_i) of outflowers and inflowers.

2.2.1. Outflowers' Sensitivity to Subsidy

Outflowers, whose primary income stems from rental earnings, exhibit heightened sensitivity to land fertility protection subsidies. This is particularly true in low-rent reciprocal networks and market mechanisms that involve high transaction costs. In interpersonal network exchanges, this subsidy plays a critical role in compensating for low rental returns. Furthermore, land not only holds economic value but also serves as a form of social security (Xu & Yu, 2023). Outflowers may face the risk of income fluctuations and increased living expenses due to the transfer of land. As a result, they have a higher demand for subsidies.

2.2.2. Inflowers' Reduced Sensitivity to Subsidy

Inflowers' revenue, particularly in large-scale operations, is less influenced by land fertility protection subsidies. Scale economies and access to other incentives, such as moderate-scale operation subsidies or tax reductions, diminish the marginal utility of fertility protection subsidies (Alauddin & Tisdell, 1988; Cui et al., 2014). Furthermore, inflowers engaging in relational network-based transfers often incur lower input costs due to informal arrangements (Ji & Zhang, 2021). However, government policies that prioritize direct subsidies for actual grain producers further reduce inflowers' dependence on fertility subsidies. Additionally, in specific regions, initiatives have been implemented to offer one-time subsidies to actual grain producers with the aim of guaranteeing their fair income. This approach has also diminished the susceptibility of new inflowers to land fertility protection subsidies.

2.3. Different Village Types of Subsidy Recipients and Land Circulation

Within a village, the behavior of each individual who outflows or inflows land is influenced by their sensitivity to the subsidy. Their behavior interacts with the decisions of other individuals, resulting in a cumulative effect. Consequently, subsidies are not always distributed equally among outflowers and inflowers owing to traditional concepts and social networks. Instead, there will always be a dominant type of subsidy recipient within a village. The preceding analysis indicates that in SO-led villages, receiving this subsidy encourages increased participation in land circulation, resulting in a higher number of outflows and further promoting the expansion of land circulation at the village level.

Therefore, we propose the following research hypothesis:

H: The scale of land circulation is larger in SO-led villages. Conversely, the scale of land circulation is smaller in SI-led villages.

3. Research Design

3.1. Study Area and Data Sources

This study selects Xintai City as the designated location for the case study for several reasons. First, Xintai is a county-level city situated in Shandong Province and exemplifies the typical characteristics of a significant agricultural county. In 2021, the primary sector in Xintai contributed 6.285 billion yuan to the overall value added in Tai'an City, representing 19.20% of the total. In addition, the rural population in Xintai was 1.0537 million. Second, Xintai has implemented Shandong Province's policy of distributing land fertility protection subsidies to actual grain cultivators. However, outflowers and inflowers receive this subsidy in practice, with a percentage of approximately 50%. Third, by the end of the "13th Five-Year Plan," Xintai had circulated a total of 480,000 mu of land, accounting for 45.3% of the total cultivated land area. This finding indicates that the phenomenon of land circulation was relatively extensive.

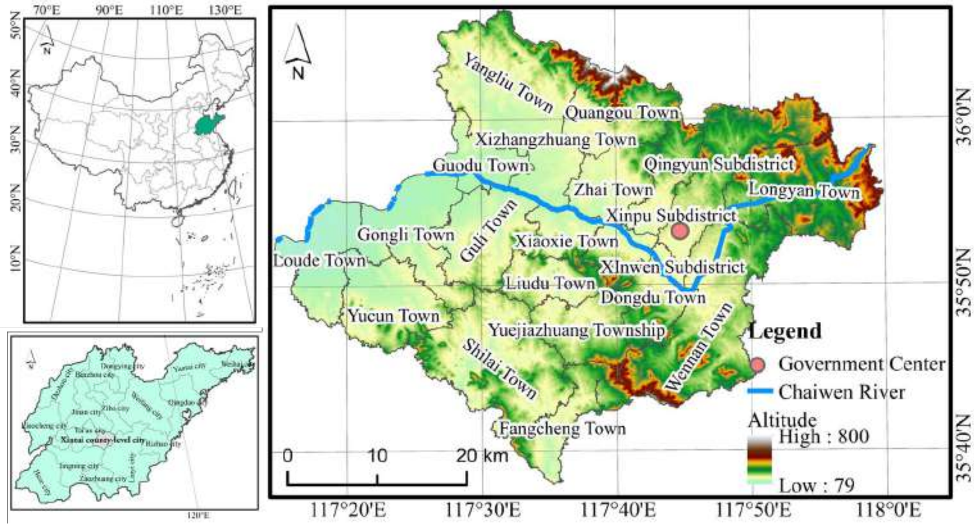


Figure 3. Research area.

Field surveys were conducted by the research group in May 2021, covering 818 villages in 20 townships and streets in Xintai City. Data were current as of the end of 2020. The screening conditions for the villages are as follows: (1) the village must have cultivated land, (2) carried out land circulation activities, and (3) have distributed land fertility protection subsidies in a timely manner. A total of 528 valid samples were obtained, accounting for 64.55% of the total number of valid samples.

Note: Although land circulation includes outflowers and inflowers, the outflow of land and the inflow of land in practice are typically balanced at the village level. Therefore, this study evaluates rural land circulation by considering the land outflow area and number of land outflow households.

3.2. Model Construction and Variable Selection

A multivariate regression model is utilized to construct the model in accordance with the research objectives and to investigate the impact of multiple independent variables on the dependent variables. The regression coefficient helps in understanding the relationship between the dependent variable (Y) and the independent variables (x_i), thereby making the model applicable to various scenarios. Equation (2) is presented as follows:

$$Y_i = C + \beta_i x_i + \sum_{j=1}^{n} \beta_j z_j + \vartheta, \tag{2}$$

where Y_i represents the dependent variable of the ith model, C is the constant term, x_i is the explanatory variable of the ith model, β_i is the regression coefficient of the explanatory variable, z_j is the jth control variable, β_j is the regression coefficient of the jth control variable, and ϑ is the random error term.

Dependent variable Y_i: The dependent variable is the proportion of land circulated area (Ji et al., 2015). The proportion is calculated as the ratio of the circulated arable land area to the total arable land area within a village.

Independent variables: The explanatory variable (x_i), which represents village types dominated by subsidy recipients, is categorized with SO-led villages assigned a value of 0 and SI-led villages assigned a value of 1, with sample sizes of 289 and 239, respectively.

Control variables z_j: These variables are derived from previous research findings and include such aspects as land circulation (Wang et al., 2020; Zhu & Yu, 2021), village situation (Wang et al., 2017; Wang & Fang, 2021), agricultural production conditions (Song et al., 2022), and locational conditions (Wang et al., 2021). The definitions and assignments for each control variable are detailed in Table 1.

Table 1. Variable indicators and descriptions.

Variables		Names	Variable Description	Expected	Count	Mean	St. Dev.
Dependent Variables		Proportion of land circulated area	Circulated arable land area/Village arable land area (%)		528	27.879	26.155
		Proportion of land circulated households	Number of households circulating land out/Total number of households (%)		528	30.692	28.671
Explanatory Variable		Village types dominated by subsidy recipients	SO-led villages = 0, SI-led villages = 1	−	528	0.450	0.498
Control Variables	Land Circulation Environment	Dominant village type	Mixed balance type = 0, Intravillage farmer dominated type = 1, Village collective dominated type = 2, Extra village dominated type = 3	+	528	1.754	0.989
		Presence of circulation incentive mechanism	No = 0, Yes = 1	+	528	0.475	0.500
		Average land circulation price in villages	Natural log of per mu land circulation price	+	528	6.354	0.610
	Village Situation	Scale of working-age labor force	Average number of labor force per household (persons/household)	−	528	1.797	0.422
		Proportion of migrant workers	Number of migrant workers/Total village population (%)	+	528	21.520	17.535
		Per capita disposable income	Average per capita income in village (10,000 yuan/person)	+	528	1.166	0.786
		Per capita arable land scale	Average per capita arable land area in village (mu/person)	−	528	1.191	0.739
	Village Agricultural Production Conditions	Proportion of non-agricultural land after circulation	Non-agricultural land area after circulated/Circulated area (%)	−	528	22.092	36.755
		Village terrain	Plains dominated= 0, Mountainous dominated= 1	+/−	528	0.345	0.476
		Presence of idle land within the village	No = 0, Yes = 1	−	528	0.225	0.418
	Locational Conditions	Distance from the village to the city center	Distance from the village to the center of Tai'an City (km)	−	528	54.428	10.911
		Presence of village public transportation	No = 0, Yes = 1	−	528	0.371	0.484

Note: The dominant village type for land direction is determined based on the classification where the cumulative area proportion of the main entrant entity exceeds 50%.

Variance inflation factors (VIFs) for all variables have been validated and confirmed to be below 5, indicating the absence of collinearity issues in the model. This finding has also been confirmed by the Pearson test. Considering the potential autocorrelation of the cross-sectional data, we employed the global Moran's I test to examine the data. The results indicated that the Z score of the global Moran's I was −0.845, with a corresponding P value of 0.398. These findings suggest that the model does not display spatial correlation and heteroscedasticity, thus indicating the suitability of using multivariate regression.

4. Results and Analysis

4.1. Spatial Differences in Village Types Dominated by Subsidy Recipients and Land Circulation

Table 2 illustrates the direction of land circulation and the proportion of village types predominantly occupied by subsidy recipients. The majority of land circulation occurs to individuals or organizations outside the village, accounting for 67.24% of the total land circulation area. This aspect is followed by the circulation between rural households within the village, covering an area of 46848 mu and accounting for 25.73% of the total land circulation area. In terms of the dominant village type for subsidy distribution, the number of SO-led villages (289) slightly exceeds the number of SI-led villages (239).

Table 2. Direction of land circulation and the proportion of village types dominated by subsidy recipients in every township street in Xintai City.

Region	Intravillage farmer area (mu)	Village collective area (mu)	Extra village individuals or organizations area (mu)	Number of SO-led villages	Number of SI-led villages
Dongdu Town	506	105	640	9	6
Fangcheng Town	1,457	160	8,523	8	14
Gongli Town	5,248	260	7,016	23	12
Guli Town	3,953	14	11,120	18	18
Guodu Town	2,835	330	3,917	24	7
Liudu Town	953	70	1,989	6	12
Longting Town	1,585	819	1,268	8	15
Loude Town	4,193	249	3,399	12	10
Qingyun Subdistrict	1,034	140	578	4	15
Quangou Town	1,079	526	10,040	24	5
Shilai Town	4,026	50	7,880	11	34
Wennan Town	2,946	1,643	6,504	27	29
Xiaoxie Town	2,619	1,365	11,173	26	1
Xinpu Subdistrict	100	430	2,968	4	6
Xinwen Subdistrict	335	1,602	2,455	7	9
Xizhangzhuang Town	6	617	10	2	1
Yangliu Town	5,978	3,532	14,975	34	15
Yucun Town	4,052	100	2,789	11	10
Yuejiazhuang Township	3,515	25	4,360	6	11
Zhai Town	428	764	20,829	25	9
Total	46,848	12,801	122,432	289	239
Proportion (%)	25.729	7.030	67.240	54.735	45.265

An assessment of the land circulation situation was conducted using ArcGIS 10.6 for Xintai City. Kernel density estimation was used to visualize the distribution of land circulation, as shown in Figure 4(a). High-density areas, represented by the color red, indicate frequent land circulation activities. These circulation activities are closely linked to farming conditions and have resulted in the formation of large-scale circulation zones on both sides of Chaiwen River. These zones are primarily concentrated in the flat terrains of plains and hills, which align with the topographical features of Xintai City.

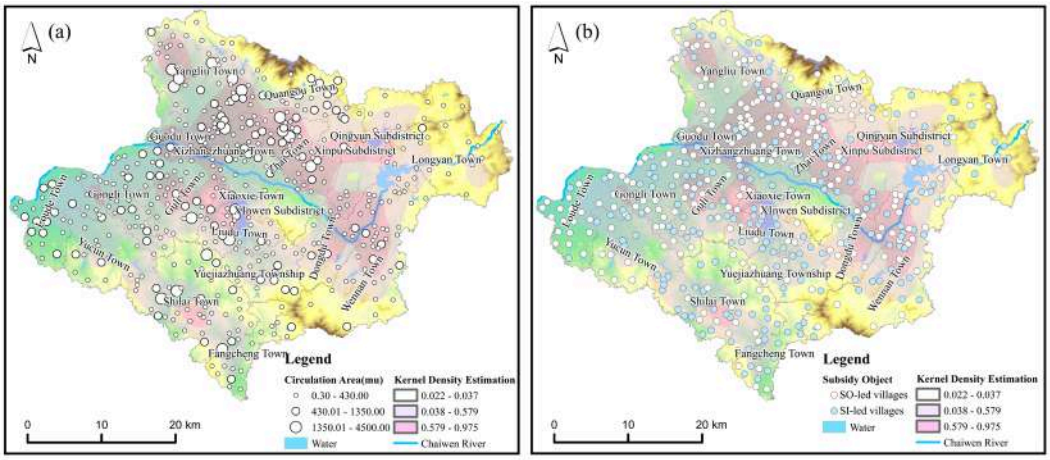


Figure 4. Spatial distribution of (**a**) land circulation and (**b**) village types dominated by subsidy recipients in Xintai City.

The observations are as follows. On the northern side of Chaiwen River, approximately 40% of the total land circulation occurs in flat terrain and the foothills of the northern mountains. The circulation foci are located at the boundaries between neighboring townships, indicating a network of interconnected land circulation. On the southern side of Chaiwen River, these areas are observed on the hillside terrains and can be clearly identified as land circulation circles. However, these areas are small in scale. In the eastern plains, the foci areas of large-scale land circulation are few. This situation can be attributed to the relative proximity to the county government or city management. Consequently, there are fewer idle lands and complex land circulation areas compared with other rural areas.

The spatial distribution of village types dominated by subsidy recipients varies. The northern and southern parts of Chaiwen River are primarily SO-led and SI-led villages, respectively (Figure 4(b)). This distribution pattern corresponds to areas where land circulation activities occur. First, in the concentrated zones of land circulation in the northern Chaiwen River, there are numerous SO-led villages, and in some towns, the percentage of villages belonging to this category exceeds 75%. Second, in the core area south of Chaiwen River, the number of SI-led villages is slightly higher than SO-led villages. In a few townships within the southernmost small land circulation circles, SO-led villages have the highest proportion. Lastly, in the eastern concentrated zones of the city, the number of SO-led and SI-led villages is approximately equal.

4.2. Analysis of the Regression Results of the Influencing Factors

Utilizing the White and corrected Breusch-Pagan tests, the results indicate that the LM statistic of the Breusch-Pagan test is 61.61, with a corresponding P-value of 0.000. The LM statistic of the White test is 179.94, and the corresponding P-value is 0.268. Since the P-value of the Breusch-Pagan test is less than the commonly used significance level (0.100), it suggests the presence of heterogeneity issues within the equation. Consequently, the feasible generalized least squares (FGLS) method was utilized to construct the model. After the necessary corrections were made, the model demonstrated P-values of 0.000, with adjusted R^2 values of 0.280 for Models 1, respectively, indicating a good fit. The regression findings are summarized in Table 3.

Table 3. Subsidy recipients and land Circulation regression.

Variable		Name		Model 1
Explanatory Variable		Village types dominated by subsidy recipients		−0.289*** (−7.390)
Control Variables	Land Circulation Environment	Dominant Village Type (Reference: Intravillage farmer dominated type)	Mixed Balance Type	0.102*** (2.682)
			Outside dominated	0.285*** (7.043)
			Extra village dominated type	0.095** (2.449)
		Presence of circulation incentive mechanism		−0.139*** (−3.674)
		Average land circulation price in villages		0.099** (2.398)
	Village Situation	Scale of working-age labor force		−0.071* (−1.851)
		Proportion of migrant workers		0.017 (0.407)
		Per capita disposable income		0.037* (0.988)
		Per capita arable land scale		−0.065 (−1.619)
	Village Agricultural Production Conditions	Proportion of non-agricultural land after circulation		−0.019 (−0.481)
		Village terrain		0.023 (0.584)
		Presence of idle land within the village		−0.087** (−2.299)
	Locational Conditions	Distance from the village to the city center		−0.038 (−0.945)
		Presence of village public transportation		−0.050 (−1.314)
Sample Size				528
R^2				0.300
Adjust R^2				0.280
F value				F=14.631, p=0.000

Note: * p<0.1, ** p<0.05, *** p<0.01, parentheses contain t-values.

Explanatory Variable: Model 1 demonstrates that the village types dominated by subsidy recipients have a statistically significant influence on land circulation, while the control variables do not exhibit any evident directional changes. The coefficient of village types dominated by subsidy recipients is −0.289, which is significant at the 1% level. This coefficient indicates a negative relationship between SI-led villages and the proportion of land circulated. This finding highlights the significant role of subsidy policy in influencing land circulation activity. In particular, land fertility protection subsidy has become an important source of income for outflowers, in addition to rent, because it serves as an economic incentive. When outflowers receive this subsidy, their psychological expectations and income needs are likely met, thereby increasing the proportion of land circulated. However, given that outflowers are no longer engaged in actual agricultural production, the subsidy policy's precise targeting expectations cannot be fully realized. This finding also validates the proposed hypothesis.

Land Circulation Environment: The regression results reveal that in contrast to the impact of the intravillage farmer-dominated type, land circulation primarily conducted by extra village domination plays a markedly significant role. This finding is indicated by the highest regression coefficient of 0.285. This aspect suggests that village marketization is considerably favorable for large-scale land circulation, particularly for circulation to entities outside of the intravillage farmer. The mixed management structure present in the village, along with the trust placed in the village collective, also contribute to land circulation. However, their effects are not as significant as those of external capital.

The observed regression coefficient of −0.139 for the circulation incentive mechanism indicates that local policies may have a negative impact on circulation. This phenomenon could be attributed to the inadequacy of local incentives in effectively reconciling the interests of outflowers and inflowers (Zheng, 2022). In addition, a considerably high land circulation price in villages, with a coefficient of 0.099, serves as a catalyst for the expansion of the land circulation scale.

Village Situation: The primary source of higher per capita disposable income in rural areas is non-agricultural labor, while rural areas have a greater amount of land resources and a higher willingness to engage in land circulation. This aspect is supported by a regression coefficient of 0.037. Conversely, a larger scale of per capita arable land, with a regression coefficient of −0.065, implies that vast expanses of arable land have altered farmers' expectations regarding their livelihoods and impeded the land circulation. By contrast, the scale of the working-age labor force and the proportion of migrant workers lack a significant influence on land circulation.

Village Agricultural Production Conditions: The presence of idle land has a significant inhibitory impact at a significance level of 1%, as indicated by a regression coefficient of −0.087. The reason is that when villages engage in land circulation, the increase in scale does not necessarily correspond to an increase in land plot size (Xie & Huang, 2022). In addition, fragmented circulation can result in idle land. In the context of limited conversion of land for non-grain purposes, no significant correlation exists between the proportion of non-agricultural land use and land circulation.

Locational Conditions: The distance of the village from the city center, which has a regression coefficient of −0.038, may be associated with limited market accessibility and markedly stable acreage owing to the significant distances. The availability of village public transportation is primarily managed at the county level. The presence of convenient transportation options enables greater flexibility in choosing between working in the county and on the land, resulting in a decrease in the number of farmers working "away from home." Therefore, this factor has a limited impact on land circulation and lacks statistical significance.

4.3. Robustness Checks

4.3.1. Robustness Test with Substitution of the Dependent Variable

Although farmers may only choose one of the contracted lands when the land is circulated, the per capita cultivated land area in the village remains fixed, and the overall amount of cultivated land circulation is dependent on the number of households involved in land circulation. On average, 31.7% of farmers in the village participated in circulation. In only 65 villages, the proportion of farmers engaging in circulation is below 5%, while in 192 villages, the proportion of farmers participating in circulation exceeds 30%. In some villages, all farmers have circulated their land. From the perspective of individuals involved in land circulation, land circulation is evidently a common occurrence within the village, with the scale and prevalence of circulation varying across villages. To ensure the reliability of the research findings, we also utilize the proportion of farmers involved in land circulation to the total number of farmers as an alternative measure for robust testing.

The regression results presented in Table 4 indicate an R^2 value of 0.238 and a P value of 0.000. This consistency with the initial regression results regarding the proportion of land circulation area highlights the reliability of the model and strengthens the validity of this study's findings and conclusions.

Table 4. Robustness test regression with the substitution of the dependent variable.

Variable	Name	Model 2
Explanatory Variable	Village types dominated by subsidy recipients	−0.218*** (−5.357)
Control Variables		Control
Sample Size		528
R^2		0.238
AdjustR^2		0.215
F value		F=10.637, p=0.000

Note: *p < 0.1, **p < 0.05, ***p < 0.01; the t values are enclosed in parentheses. The same notation applies below the table.

The regression analysis provides additional evidence with a statistically significant coefficient of −0.218 at the 1% level. SI-led villages have an impact on restricting land circulation, whereas land circulation activity in SO-led villages is more pronounced. This reverification of the research hypothesis reinforces this study's findings.

4.3.2. Subsample Robustness Test

Given the diversity of land circulation entities in Xintai City and variations in behaviors and influencing factors among different circulation entities, the impact of subsidies on internal circulation may differ from that on external or collective circulation. In reality, 378 villages have engaged in land circulation to extra village individuals or organizations, resulting in a cumulative area of 122,432 mu. These circulations have led to the cultivation of cash crops and fruit trees by the recipients, resulting in significant economic benefits and facilitating widespread land circulation. By contrast, 317 villages experienced land circulation solely among farmers within their own villages, amounting to a combined area of 46,848 mu, with the highest level of non-contractualization observed (Table 2, Figure 4). Following these circulations, the land was predominantly used for large-scale cultivation of grain crops. Lastly, 85 villages had their land circulated to village collectives, representing the smallest amount of land circulation, totaling 12,801 mu. Thus, the entire sample was divided into three subsamples based on the different entities: intravillage farmer circulated, extra village individuals and enterprises circulated, and village collective circulated. This division resulted in the creation of Models 3, 4, and 5. The results indicate that all explanatory variables passed the significance test in the subsamples, as outlined in Table 5.

Table 5. Robustness test regression results for the subsample.

Variable	Name	Model 3	Model 4	Model 5
Explanatory Variable	Village types dominated by subsidy recipients	−0.178*** (−3.134)	−0.345*** (−3.312)	−0.194*** (−3.955)
Control Variables		Control	Control	Control
Sample Size		317	378	85
R^2		0.161	0.379	0.226
AdjustR^2		0.119	0.244	0.193
F value		F=3.834, p=0.000	F=2.804, p=0.002	F=7.027, p=0.000

Regardless of the type of circulation, SI-led villages suppressed the scale of land circulation, thereby confirming the research hypothesis. However, the impact of this effect varies across different village types, dominated by subsidy recipients. In cases where land is circulated to intravillage farmers, SI-led villages experience a slight hindrance in land circulation, reflecting the complexity of internal land circulation dynamics. The most significant inhibitory effect is observed in the circulation of land to village collectives. Conversely, for circulation involving extra village individuals and enterprises, SI-led villages have significantly strengthened their inhibitory effect on land circulation.

4.3.3. Propensity Score Matching Test

We utilize a propensity score matching (PSM) approach to address potential biases that may arise from self-selection and could potentially distort the empirical findings. The villages are divided into control groups (SO-led villages) and treatment groups (SI-led villages), and nearest neighbor matching and radius matching methods are utilized for analysis. The PSM test confirms the previous results, even after accounting for sample selection biases. The evidence strongly supports the hypothesis that the scale of circulation in SO-led villages is larger.

Table 6. Results of the robustness test regression in the PSM analysis.

Methods	Difference (ATT)	Standard Errors	t	P
Nearest Neighbor Matching	−15.243	2.127	−3.765	0.000
Radius Matching	−13.362	2.127	−5.187	0.000

4.4. Moderating Effect of Subsidy and Circulation Incentives

Considering that current land circulation incentives primarily rely on financial subsidies, there may be interaction effects between these incentives and land fertility protection subsidies. To examine this, we constructed an interaction term between the two variables. Specifically, village types dominated by subsidy recipients and the presence of circulation incentive mechanisms were encoded as dummy variables, excluding a baseline category to avoid the dummy variable trap. After centralizing the data, we formulated Model 6 (Table 7). The adjusted R^2 of the model is 0.263, with an F-value of 12.740 and a P-value of 0.000, indicating that the model is statistically significant overall.

Table 7. Interaction regression results: village types dominated by subsidy recipients and circulation Incentives.

Variable	Name	Model 6
Explanatory Variable	Village types dominated by subsidy recipients	−0.294*** (−7.509)
	Presence of circulation incentive mechanism	−0.140*** (−3.690)
	Village types dominated by subsidy recipients × Presence of circulation incentive mechanism	0.054 (1.411)
Control Variables		Control
Sample Size		528
R^2		0.286
Adjust R^2		0.263
F value		F=12.740, p=0.000

The results show that, compared to Model 1 without the interaction term, subsidies allocated to SI-led villages have a more significant inhibitory effect on land circulation scale. The standardized regression coefficient of the interaction term is 0.054, suggesting that the presence of circulation incentives in SI-led villages increases the average land circulation area by 0.054 units. Although this indicator did not pass the test of statistical significance, it implies that circulation incentives do not substantially alter the effect of dominant subsidy recipient types on land circulation outcomes. Nonetheless, it hints that circulation incentives might partially offset the positive effect of subsidies provided to outflowers on promoting land circulation.

5. Conclusions and Discussion

5.1. Conclusions

In the initial stages, the scope and participants involved in China's agricultural land circulation were limited, resulting in minimal conflict between the distribution of subsidies and land circulation. However, as the distinction between contract rights for cultivated land circulation and management rights became markedly apparent, conflicts have significantly increased. This study aims to further classify the "agricultural support and protection subsidy" and focuses on the impact between different village types dominated by recipients of the land fertility protection subsidy and land circulation. To examine this phenomenon and its impact, data from 528 villages in Xintai City were analyzed. The main findings of this study are as follows.

(1) The scale of land circulation in SO-led villages is considerably large. From the perspective of the micro decision-making body, this subsidy serves as additional income that increases farmers' willingness to give up contracted land. However, the goals of the policy to protect soil fertility and achieve "precision production" have not been achieved because farmers are no longer involved in agricultural production.

(2) Different entities participating in circulation are affected by subsidy distribution in significantly different ways. When land is circulated to intravillage farmers, the circulation scale is relatively small, and SI-led villages have a markedly small effect in inhibiting the land circulation scale. By contrast, when the land is circulated to extra village individuals and enterprises, the land circulation scale in SO-led villages is larger and the promotion effect is stronger.

(3) Such factors as the dominant village type in the direction of land circulation, average land circulation price in villages, and per capita disposable income have a positive influence on the land circulation scale. Conversely, the circulation incentive mechanism, scale of the working-age labor force, and idle land within the village will hinder land circulation on a large scale.

5.2. Policy Implications and Discussion

Against the backdrop of China's current rural labor outflow resulting from urbanization and the aging of the rural labor force, the shift toward moderate-scale operations emerges as a crucial direction for agricultural development in China. In this context, the mechanism for distributing land income plays a pivotal role. To maximize the effectiveness of agricultural subsidies and facilitate the expansion of land operations, this study's findings suggest several policy recommendations.

(1) The current land fertility protection subsidy is intended to preserve the quality of land. However, in the land circulation context, this subsidy has become an additional financial advantage. The policy reform of the land fertility protection subsidy has not ensured that the subsidy received by the actual cultivators is consistent with their distribution. This situation

has hindered the transition from a universal subsidy policy to a targeted one. The conclusions drawn from the detailed agricultural support and protection subsidies differ from conventional subsidy recommendations, suggesting that the subsidy should be distributed to the actual cultivators. This difference arises because the land fertility protection subsidy, compared with the moderate-scale operation subsidy, targets different audiences, scales, and subsidy methods. Despite concerns from some quarters that distributing land fertility protection subsidies to outflowers may reduce enthusiasm among actual cultivators and potentially lead to the waste of agricultural resources, this subsidy awarded to outflowers has objectively intensified land circulation and is conducive to the scale of land management. This finding is consistent with the state's increasing investment in grain production and effort to restrict the abandonment of cultivated land.

Land fertility protection subsidy, compared with its original intention, has been transformed into a form of property income for farmers who have contracting rights. This transformation has resulted in a decrease in the effectiveness of the land quality protection policy. To achieve the goals of the policy, policymakers must coordinate the distribution mechanism of land income. A gradual reduction or even elimination of this subsidy to outflowers should be considered. Alternatively, subsidies could be restricted to land that has been successfully transferred and is being effectively utilized. Ultimately, land fertility protection subsidies should be targeted toward inflowers to achieve a "precision policy" reform that aligns with the goals of effective resource allocation and agricultural sustainability.

(2) The incentive mechanism for land circulation in the investigated region has not had a positive impact; instead, it has hindered land circulation. This effect is particularly pronounced when the subsidy is allocated to outflowers, as the guaranteed short-term income reduces their motivation to engage in land circulation.

First, the design of incentive measures should be adjusted based on the specific circumstances of subsidy implementation. Given the variations in land circulation status and agricultural development across regions, incentive mechanisms should account for regional differences. In areas with high circulation rates and advanced agricultural modernization, reducing direct subsidies and increasing support for inflowers may prove more effective. Conversely, in regions with low circulation rates, incentives should focus on facilitating outflowers' transition to ensure smoother land transfers. This differentiated incentive strategy allows for flexible policy adjustments tailored to local conditions, thereby preventing resource wastage caused by one-size-fits-all subsidy distribution.

Second, it is important to establish robust mechanisms for monitoring and adjusting incentives and subsidies to ensure their long-term effectiveness. The presence of incentive mechanisms in SI-led villages is beneficial for increasing the area of land circulation. Therefore, in SI-led villages, this can be achieved by providing productive subsidies or support for facility construction to encourage the inflow of land and promote efficient management. For instance, special subsidies for land integration can be implemented to offer comprehensive incentives, including infrastructure development, technical training, and financial assistance to those who participate in inflowers. In SO-led villages, incentives for outflowers should be linked to the progress of land transfers facilitated by outflowers. For example, outflowers could receive one-time subsidies and additional rewards after successfully transferring their land to inflowers. In this manner, the outflower can not only ensure specific economic interests but also motivate individuals to actively engage in land circulation.

Although this study has exerted effort to control various confounding variables to minimize the influence of endogeneity, there is still a possibility of a certain level of causal endogeneity in relation to the distribution of subsidy and land circulation. Additionally, due to data limitations, moderate-scale operation subsidy was excluded from the analysis. This omission prevents consideration of the potential interactions between different subsidy schemes, meaning the results cannot fully capture the combined effects of all agricultural subsidies on land circulation decisions. However, the findings of this research provide initial insights into the effects of land fertility protection subsidies on land circulation behavior. In the future, additional comprehensive research with complete data or the utilization of alternative methodologies could be conducted to accurately analyze the impact pathways connecting land fertility protection subsidy and other forms of agricultural support to the expansion of lands.

CRediT Author Statement: Zehao Qiao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, and Writing – review & editing; **Maojun Wang:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, and Writing – review & editing; **Tao Liu:** Conceptualization, Funding acquisition, Investigation, and Methodology; **Guangzhong Cao:** Funding acquisition, Project administration, Resources, and Supervision.

Data Availability Statement: The data for this study is available upon request.

Funding: This research was funded by The National Key Research and Development Program of China [grant number 2018YFD1100803] and National Natural Science Foundation of China (NSFC) [grant number 42371201].

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgments: The authors would like to express their sincere gratitude to the anonymous reviewers and the editor for their insightful comments and constructive suggestions, which have greatly contributed to improving the quality and clarity of this manuscript. Additionally, we express our gratitude to Ms. Yunling Chen from Sun Yat-sen University for her invaluable guidance during the process of writing this paper.

References

Alauddin, M., & Tisdell, C. (1988). Impact of new agricultural technology on the instability of foodgrain production and yield: Data analysis for Bangladesh and its districts. *Journal of Development Economics*, *29*(2), 199–227. https://doi.org/10.1016/0304-3878(88)90035-1

Andrews, M. (2021). The Farmer-Input Subsidy Program (FISP) does not service the poor. *Development*, *64*, 288–291. https://doi.org/10.1057/s41301-021-00317-w

Ayala-Cantu, L., & Morando, B. (2020). Rental markets, gender, and land certificates: Evidence from Vietnam. *Food Policy*, *94*, 101842. https://doi.org/10.1016/j.foodpol.2020.101842

Cui, N., Song, X., & Yu, X. (2014). Development constraints and suggestions for new agricultural production and management entities. *Jiangxi Social Sciences*, *34*(3), 52–57.

Ellis, F. (2006). *Peasant economics: Peasant household agricultural and agriculture development* (J. Hu, Trans.). Shanghai People's Publishing House. (Original work published 1988)

Fan, P., Mishra, A. K., Feng, S., Su, M., & Hirsch, S. (2023). The impact of China's new agricultural subsidy policy on grain crop acreage. *Food Policy*, *118*, 102472. https://doi.org/10.1016/j.foodpol.2023.102472

Fang, T., Zhou, Y., Wang, L., Shi, D., & Duan, X. (2024). The impact of multiplex relationships on households' informal farmland transfer in rural China: A network perspective. *Journal of Rural Studies*, *112*, 103419. https://doi.org/10.1016/j.jrurstud.2024.103419

Guo, L., Li, H., Cao, X., Cao, A., & Huang, M. (2021). Effect of agricultural subsidies on the use of chemical fertilizer. *Journal of Environmental Management*, *299*, 113621. https://doi.org/10.1016/j.jenvman.2021.113621

Huang, J., Wang, X., Zhi, H., Huang, Z., & Rozelle, S. (2011). Subsidies and distortions in China's agriculture: Evidence from producer-level data. *Australian Journal of Agricultural and Resource Economics*, *55*(1), 53–71. https://doi.org/10.1111/j.1467-8489.2010.00527.x

Ji, X., Qian, Z., & Ge, Y. (2015). Can agricultural subsidies promote the transfer of land contracting right: Based on the household survey data in the four provinces of JiangSu, HuBei, GuangXi and HeiLongJiang. *Issues in Agricultural Economy*, *36*(05). https://doi.org/10.13246/j.cnki.iae.2015.05.006

Ji, X., & Zhang, H. (2021). How does social trust affect farmers' land transfer-out behavior? *China Land Science*, *35*(10), 45–54. https://doi.org/10.11994/zgtdkx.20211012.103035

Liao, H. (2012). The part-time work of farmers and its impact on the use rights transfer of the agricultural land. *Journal of Management World*, (05). https://doi.org/10.19744/j.cnki.11-1235/f.2012.05.006

Lin, W., & Huang, J. (2021). Impacts of agricultural incentive policies on land rental prices: New evidence from China. *Food Policy*, *104*, 102125. https://doi.org/10.1016/j.foodpol.2021.102125

Liu, Z., & Liu, L. (2016). Characteristics and driving factors of rural livelihood transition in the east coastal region of China: A case study of suburban Shanghai. *Journal of Rural Studies*, 43, 145–158. https://doi.org/10.1016/j.jrurstud.2015.12.008

Qi, X., & Yang, Y. (2022). Rural household's livelihood differentiation, land transfer and farmers' income growth in western China. *Journal of Arid Land Resources and Environment*, *36*(08), 38–45. https://doi.org/10.13448/j.cnki.jalre.2022.197

Qian, L., & Hong, M. (2016). Non-agricultural employment, land transfer and changes in agricultural production efficiency: An empirical analysis based on CFPS. *China Rural Economy*, (12), 2–16. https://jtp.cnki.net/bilingual/detail/html/ZNJJ201612001

Song, K., Liu, W., Wei, X., & Zhong, S. (2022). Influence of agricultural outsourcing operation on land transfer rent: An empirical analysis based on farmer survey data in 3 provinces (Municipality). *Economic Geography*, *42*(03), 133–140 . https://doi.org/10.15957/j.cnki.jjdl.2022.03.014

Sun, F., & Lv, Y. (2012). Research on the income-increasing effect of my country's agricultural subsidy policy in the central and western regions. *Knowledge Economy*, (02), 79–81. https://doi.org/10.15880/j.cnki.zsjj.2012.02.106

Tian, G., Duan, J., & Yang, L. (2021). Spatio-temporal pattern and driving mechanisms of cropland circulation in China. *Land Use Policy*, *100*, 105118. https://doi.org/10.1016/j.landusepol.2020.105118

Veeck, G., & Shui, W. (2011). China's quiet agricultural revolution: Policy and programs of the new millennium. *Eurasian Geography and Economics*, *52*(2), 242–263. https://doi.org/10.2747/1539-7216.52.2.242

Wang, H., & Fang, Y. (2021). Livelihood transition and sustainability of rural households in mountainous area: A case of YaoZhan town in WeiChang county of HeBei Province. *Economic Geography*, *41*(03), 152–160. https://doi.org/10.15957/j.cnki.jjdl.2021.03.016

Wang, J., Xin, L., & Wang, Y. (2020). How farmers' non-agricultural employment affects rural land circulation in China? *Journal of Geographical Sciences*, *30*(3), 378–400. https://doi.org/10.1007/s11442-020-1733-8

Wang, Q., Dang, H., & Yu, J. (2021). How does grain price affect land rent and revenue distribution: Based on rural household panel data from 2013 to 2019. *Chinese Land Science*, *35*(8), 57–66. https://doi.org/10.11994/zgtdkx.20210817.091614

Wang, Y., Li, X., & Xin, L. (2017). The impact of agricultural labor force age on land transfer according to CHIP2013. *Resource Science*, *39*(8), 1457–1468. https://doi.org/10.18402/resci.2017.08.03

Wang, Y., Li, X., Xin, L., Tan, M., & Jiang, M. (2018). Regional differences of land circulation in China and its drivers: Based on 2003–2013 rural fixed observation points data. *Acta Geographica Sinica*, *73*(3), 487–502. https://doi.org/10.11821/dlxb201803008

Xie, H., & Huang, Y. (2022). Impact of non-agricultural employment and land transfer on farmland abandonment behaviors of farmer: A case study in Fujian-Jiangxi-Hunan Mountainous Areas. *Journal of Natural Resources*, *37*(2), 408–423. https://doi.org/10.31497/zrzyxb.20220210

Xu, G., & Yu, J. (2023). Why does the rural land circulation develop in an internal way? Based on the perspective of “Instability” and “Social Security”. *Rural Economy*, (7), 36–43.

Xu, Q., Lu, Y., & Zhang, H. (2020). Have agricultural support and protection subsidies encouraged large-scale farmers to grow grain? An analysis based on data from fixed observation points of the ministry of agriculture and rural affairs in China. *Chinese Rural Economy*, (4), 15–33. https://qikan.cqvip.com/Qikan/Article/Detail?id=7101566978

Yi, F., & McCarl, B. (2018). Increasing the effectiveness of the Chinese grain subsidy: A quantitative analysis. *China Agricultural Economic Review*, *10*(4), 538–557. https://doi.org/10.1108/caer-08-2016-0136

Yu, W., & Jensen, H. G. (2010). China’s agricultural policy transition: Impacts of recent reforms and future scenarios. *Journal of Agricultural Economics*, *61*(2), 343–368. https://doi.org/10.1111/j.1477-9552.2010.00242.x

Zhang, Y., Wang, Y., & Bai, Y. (2019). Knowing and doing: The perception of subsidy policy and farmland transfer. *Sustainability*, *11*(8), 15, 2393. https://doi.org/10.3390/su11082393

Zheng, K. (2022). Rural land transfer incentive and supervision mechanism from the perspective of information asymmetry. *Agricultural Economy*, (05), 105–106.

Zhu, Y., & Yu, J. (2021). Impact of poverty alleviation relocation on farmers’ income and income gaps: A case study of 1680 households in Southern Shaanxi. *Resource Science*, *43*(10), 2013–2025. https://doi.org/10.18402/resci.2021.10.07

Agricultural & Rural Studies

Article

Investigating Farmers' Intention to Adopt Renewable Energy Technology for Farming: Determinants of Decision Making in Northern Ghana

Ransford Teng-viel Karbo [1]*, Lynn J. Frewer [1]*, Francisco J. Areal [1,2,4], Albert Boaitey [1], Glyn Jones [1,3] and Guy Garrod [1]

1 School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom; Albert.Boaitey@newcastle.ac.uk (A.B.); guy.garrod@newcastle.ac.uk (G.G.)
2 Newcastle Business School, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom; francisco.areal@northumbria.ac.uk
3 Fera Science Ltd., York YO41 1LZ, United Kingdom; glyn.d.jones@fera.co.uk
4 School of Agriculture Policy and Development, University of Reading, Reading RG7 1WJ, United Kingdom
* Correspondence: r.t.karbo2@newcastle.ac.uk (R.T.-v.K.); Lynn.Frewer@newcastle.ac.uk (L.J.F.)

Abstract: Integrating renewable energy into agricultural practices can result in environmental and economic benefits. In Ghana, renewable energy resources that can support agronomic activities include solar energy and biomass. Although policies and interventions that promote Ghanaian renewable energy development and implementation currently exist, it is not yet understood which factors motivate farmers to adopt renewable energy technologies within the country's agricultural sector. This research aimed to identify which psychological and economic factors influence Northern Ghanaian farmers' intention to adopt renewable energy technology within agriculture. A survey was administered to farmers (n = 418) in Lawra Municipality in Northern Ghana, where farming represents the main source of income. Structural Equation Modelling was applied to test and validate an adapted theoretical model (the Decomposed Theory of Planned Behaviour) to identify which factors are associated with farmers' likelihood to adopt renewable energy technology. Attitude, Perceived Behavioural Control, Perceived Usefulness, Perceived Ease of Use, Compatibility, Risk, Peer and External Influences, Self-efficacy, Resource-Facilitating Conditions, and Technology-Facilitating Conditions were positive and significant factors influencing farmers' intention to adopt renewable energy technology. However, subjective norms did not positively predict farmers' intentions. The results suggest that to ensure the widespread adoption of renewable energy in Ghanaian agriculture, policies and interventions could usefully align with the psychological attributes of farmers. Policymakers should develop and implement appropriate policies to encourage sustainable technology adoption in agriculture, including tax and credit subsidies and green financing frameworks to increase support for farmers to adopt renewable energy technology.

Keywords: renewable energy; technology; Decomposed Theory of Planned Behaviour; lower-to-middle-income country; LMIC; agriculture

Citation: Karbo, R. T.- viel, Frewer, L. J., Areal, F. J., Boaitey, A., Jones, G., & Garrod, G. (2025). Investigating Farmers' Intention to Adopt Renewable Energy Technology for Farming: Determinants of Decision Making in Northern Ghana. *Agricultural & Rural Studies*, *3*(1), 25. https://doi.org/10.59978/ar03010003

Received: 23 September 2024
Revised: 24 October 2024
Accepted: 30 December 2024
Published: 28 February 2025

1. Introduction

Since the ratification of the Kyoto Protocol and the Paris Agreement, many countries have prioritised sustainable energy technology and developed and implemented policies aimed at decreasing carbon emissions and improving national energy security (Pestisha et al., 2023). Renewable energy is important from an environmental perspective as it utilises resources that can generate clean energy with minimal environmental effects (Adams & Nsiah, 2019; Jin & Kim, 2018; Wesseh & Lin, 2017). Renewable energy can contribute to global energy requirements given its regenerative characteristics, including solar, wind, biomass, hydro, geothermal, wave and tidal energy sources (Chel & Kaushik, 2011). In addition to the environmental benefits, renewable energy is associated with stable market conditions when compared to, for example, the volatility in prices of fossil fuels such as crude oil (Ali et al., 2012; Pestisha et al., 2023) and is more likely to ensure energy security (Sotnyk et al., 2021). However, the potential benefits across industry different sectors cannot be realised unless stakeholders and end-users widely adopt renewable energy. It is important to understand the socio-economic factors which determine whether farmers will adopt new technologies with the potential to deliver environmental benefits into their agricultural practices. This research used a modified version of the Decomposed Theory of Planned Behaviour to identify which psychological and economic factors influence Northern Ghanaian farmers' intention to adopt renewable energy technology within agriculture. Although the use of sustainable energy in agriculture has been identified as important in Ghanaian policy (Karbo et al., 2022), adoption by stakeholders within the sector has been slow.

Energy is needed in economically influential sectors, including agriculture. Agriculture directly supports food production and so is needed for national and global development (Best, 2014; Lawal, 2023). Due to increased mechanisation within the sector, agriculture has become increasingly dependent on energy and has been estimated to contribute between 14 to 30 percent of global greenhouse gas (GHG) emissions (Khan et al., 2018; Lenka et al., 2015; Liu et al., 2017b; Richards et al., 2018). The manufacture and application of agricultural inputs, use of fossil-fuelled farm machinery, poor practices in land preparation and agronomic activities, and livestock production represent significant contributors to GHG emissions (Bell et al., 2014; Bellarby et al., 2013; Blandford & Hassapoyannes, 2018; Lenka et al., 2015). This trend will continue if the current level of energy use intensity in agriculture is increased in line with greater agronomic mechanisation and automation which is required to deliver future food security requirements (Lenka et al., 2015; Liu et al., 2017a). Food demand is projected to increase based on increasing population, and this will potentially drive the increase in energy use in agriculture because of the need to increase agricultural efficiency through technological applications which may use more energy (Harvey & Pilgrim, 2011; Röös et al., 2017).

Renewable energy utilisation is needed to decrease the agricultural sector's carbon emissions and ensure energy self-sufficiency for farmers and other agricultural value chain actors (Abaka et al., 2017; Jebli & Youssef, 2017; Pestisha et al., 2023). There is evidence that renewable energy resources can support future agricultural energy needs and, at the same time, promote sustainable agricultural production (Martinho, 2018; Smith & Gregory, 2013). Renewable energy can be used to support farm-based activities such as generating electricity for lighting, powering water pumps, providing heating in greenhouse farming, drying, heating and cooling for storage purposes on farms (Abaka et al., 2017; Ali et al., 2012; Bayrakcı & Koçar, 2012). Agriculture can also create raw materials in the form of biomass resources (i.e., crops/livestock residue/bioenergy crops) that can support energy generation to be used for various agricultural activities (Best, 2014). Thus, as the reliability of the renewable energy supply is improved, alternative income sources can be generated for farmers and farms (Fami et al., 2010). Given that agronomic, social, and economic benefits can be provided by renewable energy sources, countries and stakeholders (e.g., policymakers, farmers, and other supply chain actors) need to develop appropriate approaches to optimise the full potential of renewable energy resources and how these are applied in the agricultural sector (Dulal et al., 2013; Elahi et al., 2022).

Governments and interested stakeholder groups have promoted the use of innovative agricultural technologies, including renewable energy technologies (e.g., solar energy and use of biomass), to farmers for adoption into their agricultural practices. It is expected that when farmers start to adopt renewable energy technologies, agronomic practices will transition from those using labour-intensive manual methods to those integrating mechanised farming due to the increased availability of energy, enabling farmers to expand farming acreages, production yields, and household income (Aryal et al., 2021; Sims & Kienzle, 2017). For example, renewable energy technology can support agronomic practices in relation to land preparation activities using biomass energy inputs such as organic fertilisers to improve soil fertility and solar water pumps to irrigate crops (Ayamga et al., 2015; Stock et al., 2023).

In Ghana, farmers are encouraged by the government including the Ministry of Food and Agriculture (Investment for Food and Jobs), Ministry of Energy (Ghana Renewable Energy Master Plan), Ministry of Environment, Science, Technology, and Innovation (National Climate Change Policy) and interested stakeholder groups (such as Peasant Farmers Association of Ghana, Centre for Indigenous Knowledge and Organisational Development, FARA, etc) to adopt innovative agricultural technologies, including renewable energy technology, to improve their farming productivity sustainably. At present, there is evidence that renewable energy technology adoption in Ghana in the agricultural sector is low, and identification of factors which may accelerate, or act as barriers to, farmers' adoption behaviours to renewable energy technologies (Asiamah et al., 2022; Karbo et al., 2022).

Previous research has identified factors which may influence farmers' adoption behaviours in relation to new technologies (e.g., see Kabwe et al., 2009; Mapemba et al., 2013; Mogaka et al., 2014; Mukherji et al., 2017; Mwakaje, 2008; Nyamwena-Mukonza, 2012; Obiero et al., 2019; Putra et al., 2019). For example, the cost of adopting technology, technology compatibility with existing agricultural practices, peer influence, perceived risk of adoption, enhanced time farming time, and extension services to educate farmers are some of the factors identified to influence farmers' technology adoption behaviour (Ambali et al., 2021; Cheteni et al., 2014; Makate, 2020; Olumba et al., 2024; Tran-Nam & Tiet, 2022). Understanding how these factors influence farmers' technology adoption behaviours can help researchers, policymakers, and other non-farmer stakeholders develop interventions to increase farmers' technology adoption (Borges et al., 2014).

This research aims to understand which psychological and perceived economic determinants influence farmers' intention to adopt renewable energy technology in Northern Ghana agriculture. Researchers have applied various theoretical approaches to understand the psychological and perceived economic determinants of farmers' technology adoption behaviours including the Diffusion of Innovation theory, the Theory of Planned Behaviour, the Expected Utility Theory, and the Decomposed Theory of Planned Behaviour (Musungwini et al., 2022; Nyairo et al., 2022; Sileshi et al., 2019; Zeweld et al., 2017b).

The Decomposed Theory of Planned Behaviour was used in this research to assess which psychological predictors may affect farmers' intention to adopt renewable energy in the context of Northern Ghana. The Decomposed Theory of Planned Behaviour was identified as a suitable theoretical approach to predict farmers' behavioural intentions to adopt renewable energy in agriculture, as previous research has validated its application in LMICs to assess agricultural technology adoption (Table 1). Application of the Decomposed Theory of Planned Behaviour provides evidence for policymakers to enable them to consider psychological factors in the development of policies and interventions aimed at improving the adoption of renewable energy technology for farming by farmers. From a theoretical perspective, the research provides evidence regarding the validity of the theory in the context of the prediction of farmers' adoption behaviours in relation to renewable energy in the context of Ghana, and potentially in a broader LMIC context.

Table 1. Selected studies in LMICs which have applied the Decomposed Theory of Planned Behaviour in agriculture.

	Aims of the Research	Country (or Countries)	Main Results	Reference
1.	To examine behavioural factors affecting the adoption of manuring of smallholder mature rubber cultivations.	Sri Lanka	A positive relationship existed between compatibility and attitude, perceived usefulness and attitude, and perceived ease of use and attitude. No relationship between relative advantage and attitude was observed.	Gunarathne et al. (2021)
2.	To investigate socio-technological factors influencing smallholder farmers' choices of agroforestry technologies in the eastern highlands of Uganda.	Uganda	The number of tree species preferred by farmers in agroforestry, and the perceived value of agroforestry were the most important factors that determined farmers' decision to adopt agroforestry technologies.	Kalanzi et al. (2021)
3.	To explore factors that influenced farmers' intention to adopt sustainable agriculture practices for coffee farming in Vietnam.	Vietnam	Farmers' intention to adopt sustainable agricultural practices was influenced by perceived social pressure, the perception of climate change, and the perceived ability to perform sustainable agriculture.	Nguyen & Drakou (2021)
4.	To understand the behavioural intentions of smallholder farmers in relation to the adoption of mechanised conservation agriculture.	Zambia	Positive attitude towards, and perceived behavioural control over, increased farmers' intention to adopt mechanised conservation agriculture.	Omulo et al. (2024)
5.	To understand smallholder farmers' behavioural intentions to adopt sustainable agriculture practices in Ethiopia.	Ethiopia	Positive attitudes and normative issues such as technical training, extension service, and social capital explain farmers' behavioural intention to adopt sustainable agricultural practices.	Zeweld et al. (2017b)

2. Research Model and Hypotheses Development

2.1. The Decomposed Theory of Planned Behaviour

The Decomposed Theory of Planned Behaviour was initially developed by Taylor and Todd (1995a) as an extension of the Theory of Planned Behaviour. Similarly, the Decomposed Theory of Planned Behaviour assumes that a behavioural intention is likely to lead to an adoption behaviour, and that interacting psychological constructs (Attitude, Subjective Norms, and Perceived Behavioural Control) predict behavioural intention (Alomary & Woollard, 2015; Shao et al., 2022). In addition to building on the Theory of Planned Behaviour, the Decomposed Theory of Planned Behaviour unifies constructs from the Technology Acceptance Model (Davis, 1989), the Theory of Planned Behaviour and the Diffusion of Innovations Theory (Ajzen, 1991). Specifically, the Decomposed Theory of Planned Behaviour includes the constructs "perceived Ease of Use" and "Perceived Usefulness" from the Technology Acceptance Model as components of "Attitude" (Davis, 1989). Perceived Compatibility, derived from the Diffusion of Innovation Theory, is also assumed to contribute to attitude (Rogers, 2003).

The Theory of Planned Behaviour has been criticised as it assumes that attitudes predict behaviours, which in turn are predicted by Subjective Norms and perceived behavioural control (Taylor & Todd, 1995a). The Decomposed Theory of Planned Behaviour addresses this criticism by decomposing the Attitude, Subjective Norms, and Perceived Behavioural Control constructs further. According to Fishbein and Ajzen (1977), attitude as a construct refers to the sentiments (positive or negative) an individual develops regarding whether to perform a particular behaviour. Subjective norms are the social pressures that are perceived to be influential, and that can influence an individual's intention to adopt or reject technology. The perceived behavioural control construct refers to the perceived ease or difficulty in performing an adoption behaviour regarding a technology.

The underlying factors that determine the three main constructs of the Decomposed Theory of Planned Behaviour. Attitude is determined by Ease of Use, Perceived Usefulness, and Compatibility. Subjective Norms are influenced by Peer and External Influences. Perceived Behavioural Control is influenced by Self-efficacy, Resource-Facilitating Conditions, and Technology-Facilitating Conditions. Table 1 provides examples of the application of the Decomposed Theory of Planned Behaviour to agriculture in LMIC countries.

2.2. Development of Hypotheses

The hypotheses were developed from the Decomposed Theory of Planned Behaviour where three primary constructs are proposed to predict Behavioural Intention: Attitude, Subjective norms, and Perceived Behavioural Control. The following hypotheses are proposed:

- H1: A positive Attitude will increase intention to adopt a renewable energy technology in farming.
- H2: Positive Perceived Subjective Norms will increase intention to adopt renewable energy technology for farming.
- H3: Higher perceived Behavioural Control will increase intention to adopt a renewable energy technology for farming.

The three primary constructs, Attitude, Subjective Norms, and Perceived Behavioural Control are decomposed into sub-constructs in the Theory (i). Three sub-constructs contribute to Attitude: These are Perceived Ease of Use, Perceived Usefulness, and Compatibility. In this research, perceived ease of use assessed the extent to which a new renewable energy technology was perceived to be convenient to understand and operate. Perceived usefulness measures the individual's expectation that (e.g.) a new technology improves the outcomes of a task or activity. Perceived compatibility assesses the suitability of (e.g.) a new technology relative to an existing technology or practice. Therefore, it is assumed that a farmer is more likely to adopt a renewable energy technology for farming if its application is perceived to be easy to understand and operate. Similarly, a farmer is more likely to adopt a technology if its operation is perceived to align with their existing agronomic practices.

The belief structure within the Decomposed Theory of Planned Behaviour is flexible and can be modified to suit different research objectives (Shao et al., 2022). An additional variable (risk) is introduced from Expected Utility Theory. Expected Utility Theory assumes that an individual's adoption behaviour is predicted by perceived risk associated with the new technology, uncertainty about the outcomes of using it, and the superior value expected from new technology adoption, in relation to whether it surpasses that of an older or existing technology (Mongin & Baccelli, 2021). This implies that a farmer compares a new technology with an existing technology or practice and is more likely to adopt the new technology if it guarantees a higher expected utility (Borges et al., 2015; Meijer et al., 2015; Schoemaker, 1982). Expected Utility (von Neumann & Morgenstern, 1953) was added to the model. It was assumed that a farmer would adopt renewable energy technology if its application is perceived to result in greater Expected Utility.

Given these assumptions, the following hypotheses have been formulated.

- H4: Greater Perceived Ease of Use will positively affect attitude to adopt renewable energy technology for farming.
- H5: Greater Perceived Usefulness will positively affect attitude toward adopting renewable energy technology for farming.
- H6: Greater perceived compatibility will positively affect attitude to adopting renewable energy technology for farming.
- H7: Lower Perceived Risk will positively affect a farmer's attitude to adopt renewable energy technology for farming.

According to Fishbein and Ajzen (1977), Subjective Norms are the social pressures that affect an individual's intention to engage in a behaviour. Subjective Norms can be deconstructed into two sub-constructs: "Peer Influence" and "External Influence". In Ghana, farmers live in communities comprised of both family and non-family members (e.g. spouses, children, and colleague farmers etc.) and are involved in various social interactions (Awuni et al., 2018). Here, Peer influence is assumed to occur when colleagues or family members within their immediate community persuade a farmer to decide whether to adopt a renewable energy technology. External influence occurs when a farmer is convinced by people outside their immediate community such as researchers, agricultural extension professionals and other non-farmer stakeholders to adopt new technology. The following hypotheses have been formulated.

- H8: Perceived peer influence (whether positive or negative) will (positively and negatively) affect subjective norm to adopt renewable energy technology for farming.

- H9: Perceived external influence (whether positive or negative) will (positively and negatively) affect subjective norm to adopt renewable energy technology for farming.

In the Decomposed Theory of Planned Behaviour, Perceived Behavioural Control is comprised of three underlying sub-constructs: Self-efficacy, Resource-Facilitating Conditions, and Technology-Facilitating Conditions. Here, Self-Efficacy refers to the ability of an individual to perform an action. For example, a farmer will adopt a new technology that is perceived to be operational without physical or psychological discomfort. Positively perceived resource and technology-facilitating conditions stimulate an intention to adopt a renewable energy technology. For farmers, resource-facilitating conditions may include perceptions that they have sufficient time, access to capital, and appropriate agronomic conditions to adopt a particular technology. Technology facilitating conditions may include the perceived availability of spare parts for equipment, access to markets, and specialist support in relation to repair equipment and machinery repair (Nyasulu & Dominic Chawinga, 2019; Taylor & Todd, 1995a). The following hypotheses are proposed.

- H10: Higher perceived self-efficacy will increase perceived behavioural control to adopt renewable energy technology for farming.
- H11: Greater perceived access to resource-facilitating conditions will increase perceived behavioural control to adopt renewable energy technology for farming.
- H12: Greater perceived access to technology-facilitating conditions will increase perceived behavioural control to adopt renewable energy technology for farming.

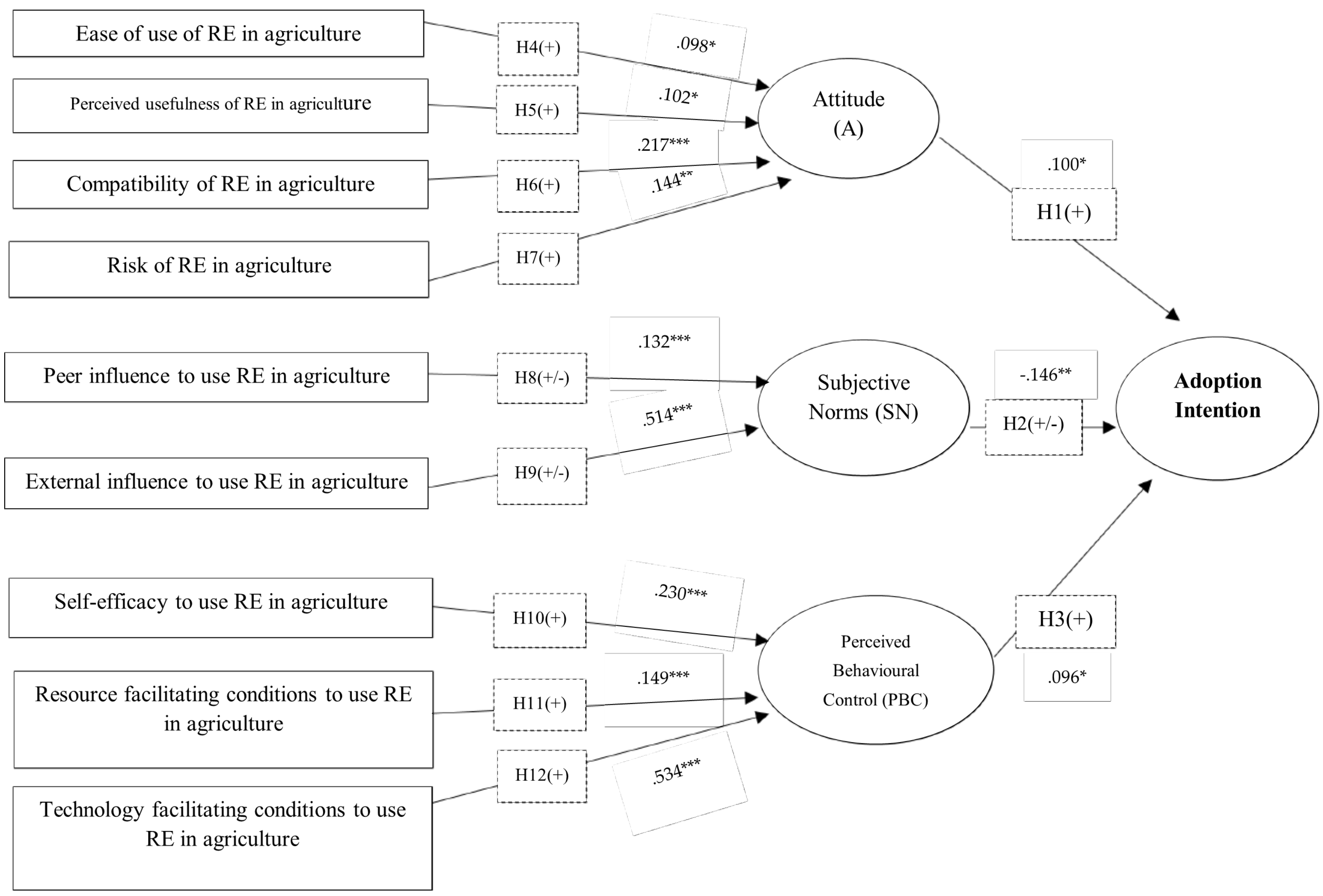


Figure 1. Constructs predicting farmers' behavioural intentions to adopt renewable energy technology (adapted from the Decomposed Theory of Planned Behaviour). The direction of the hypothetical relationship is indicated in brackets for each Hypothesis. (RE = Renewable Energy) Adapted and modified from Taylor and Todd (1995a).

3. Materials and Methods

3.1. Data Collection

A survey was designed to collect data (May 2023) from farmers in the Upper West Region of Northern Ghana where agriculture is the main source of livelihood. The survey used a 5-point Likert scale (i.e., strongly disagree to strongly agree) to measure variables, including constructs contributing to Attitude factors (Perceived Usefulness, Perceived Ease of Use, Perceived Compatibility, and Perceived Risk), Subjective Norms (Perceived Peer and External Influences), and Perceived Behavioural Control (Perceived Self-Efficacy, Perceived Technology Facilitating Conditions, and Resource Facilitating Conditions). The survey was developed in English, and an online version was created using the KobToolbox application. Ethical approval was obtained from the Faculty of Science, Agriculture and Engineering prior to data collection, Newcastle University (Ref: 32218/2023; 11/05/2023).

The survey had five sections: 1) General/background information, 2) Energy use in agriculture, 3) Socioeconomic drivers and barriers, 4) Psychological drivers and barriers, and 5) External drivers facilitating sustainable energy adoption. Yamene's formula (Bala & El-jajah, 2019) was used to determine the sample size indicating that a total of 429 farmer interviews were required. A systematic sampling technique was used to select farmers to participate in the survey. The participant sample was selected from the overall farmer population within the sampling area at regular intervals (Singh & Singh, 1977). Farmers were identified through household sampling. Following the initial random selection of a household within the sampling frame, subsequent households were selected after every 10th interval count of households. The systematic sampling technique was used due to its simplicity in terms of application, and robustness in relation to obtaining representativeness within a population (Castillo, 2009; Elsayir, 2014; Opsomer et al., 2012). The head of a selected household was the first point of contact and was asked for permission prior to an interview being conducted with a participant farmer. This is in line with the traditional entry protocol when visiting households in the study area. Farmer participants were targeted through households because 80 percent of households in the research area engaged in farming. One farmer was interviewed per household. Therefore, household heads (predominantly represented by male farmers) dominated the participants sampled).

3.2. Research Area

Lawra Municipality was selected for the research. Agriculture is the major economic activity in this municipality, with about 80 percent of the working population being employed in agriculture-related work (Lawra Municipal Assembly, 2018). Agriculture in this area is predominantly undertaken within smallholdings, mainly to provide food for household consumption. Crops cultivated include maize, millet, groundnuts, soya bean and cowpea. In addition, livestock farming includes goats, pigs, sheep, poultry, and cattle. Depleted soil fertility, erratic rainfall patterns, the occurrence of agricultural pests and diseases, farmers' limited access to credit, and inadequate access to technology, extension services, and markets threaten farmers only source of livelihood and food security (Lawra Municipal Assembly, 2018).

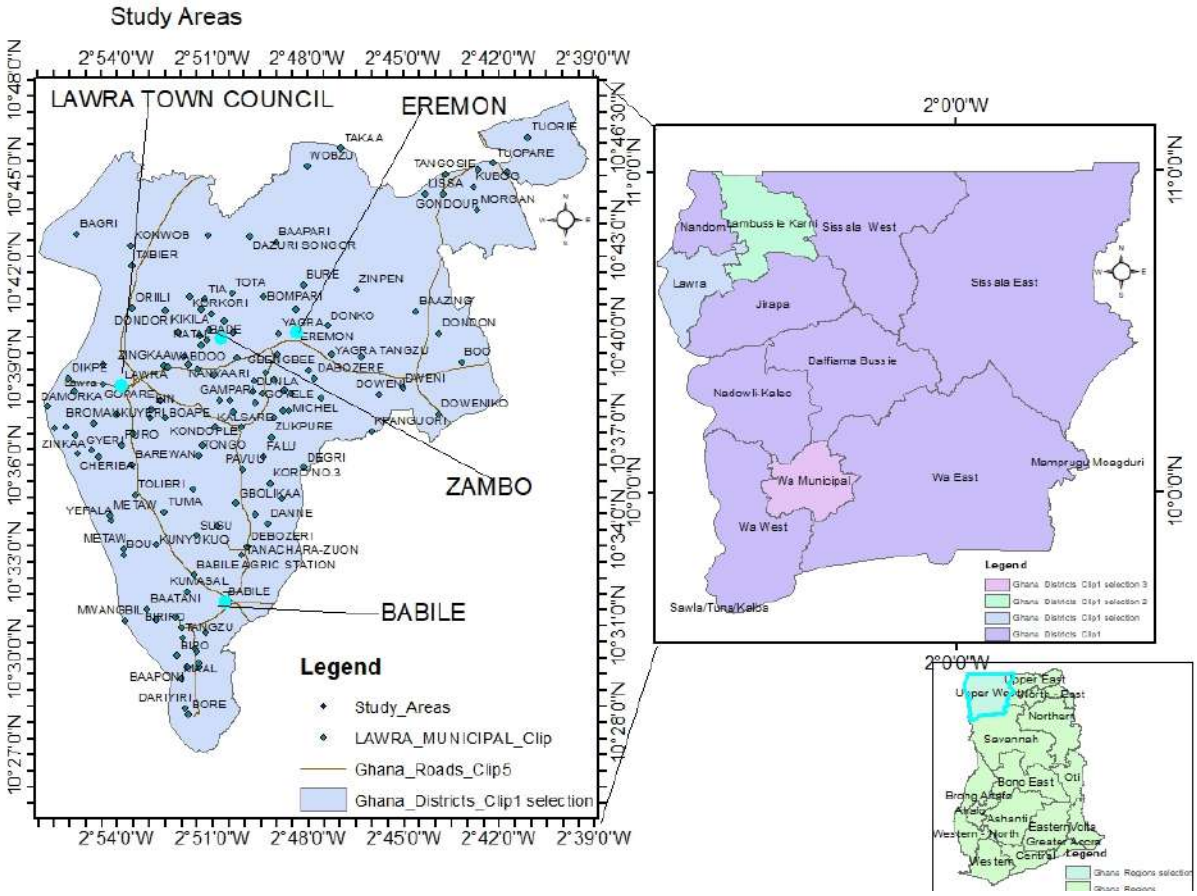


Figure 2. Map of the research area.
Source: Author's own (2023).

3.3. Data Analysis

A total of 429 farmer survey interviews were conducted. Following the exclusion of incomplete surveys, 418 completed responses were obtained and subsequently included in the analysis. A descriptive analysis of the demographic and background attributes of the farmers was analysed using SPSS version 29. Structural Equation Modelling (SEM) was conducted using AMOS 29 to test the research hypotheses (https://www.ibm.com/support/pages/downloading-ibm-spss-amos-29-0). SEM was applied to assess the relationship between variables or constructs in the adapted research model (Savalei & Bentler, 2006; Ullman & Bentler, 2012), allowing the assessment of complex and multiple relationships underpinning numerous variables, and testing the predictivity of theoretical models using empirical data (Bollen & Noble, 2011; Chin, 1998).

Confirmatory factor analysis was initially applied to assess the validity of the constructs included in the research model (Hoyle, 2000; Stapleton, 1997; Stevens, 1996). Confirmatory factor analysis as opposed to Exploratory factor analysis was applied because the underlying factors contributing to constructs used in the model had been identified and validated in previous research (Bagheri et al., 2016; Fishbein & Ajzen, 1977; Musyoki et al., 2022; Rezaei et al., 2020; Sharifzadeh et al., 2017; Venkatesh et al., 2003).

3.4. Definition of Measurement Scales

A total of 45 items were included in the measurement scales used to measure the constructs. Each construct consisted of at least three items in the form of a statement and scored using a Likert scale from 1 to 5 (where 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree). Table 2 summarises items and constructs measured in the research.

Table 2. Items used to measure constructs in the research.

Constructs	Item	Sources
Perceived Ease of Use	EU1 (It will be stress-free for me to use solar technology for farming). EU2 (I will be comfortable operating solar technology alone). EU3 (It will be stress-free for me to use biomass technology for farming).	Bagheri et al., 2016; Davis, 1989; Rezaei et al., 2020
Perceived Usefulness	PU1 (Using solar technology will increase my yields). PU2 (Using solar technology will increase my profits). PU3 (Using biomass technology will increase my yields). PU4 (Using biomass technology will increase my profits).	Davis, 1989; Rezaei et al., 2020
Perceived Compatible	CT1 (Adopting solar technology suites the type of farming I practice). CT2 (Adopting solar technology is compatible with indigenous farming practices). CT3 (Adopting biomass technology suites the type of farming I practice).	Rogers, 2003; Sharifzadeh et al., 2017
Perceived Risk	RK1 (Using solar technology has no effect on my farm income). RK2 (Using biomass technology has minimal or no effect on my farm yields). RK3 (Using biomass technology has no effect on my farm income).	Musyoki et al., 2022
Perceived Peer Influence	PI1 (A family member will approve the use of solar technology for farming). PI2 (A neighbour will approve the use of solar technology for farming). PI3 (A family member will approve the use of biomass technology for farming). PI4 (A neighbour will approve the use of biomass technology for farming).	Taylor & Todd, 1995b
Perceived External Influence	EI1 (An agricultural extension officer will approve the use of solar technology for farming). EI2 (Members of a farmer cooperative/association will approve the use of solar technology for farming). EI3 (An agricultural extension officer will approve the use of biomass technology for farming). EI4 (Members of a farmer cooperative/association will approve the use of biomass technology for farming).	Taylor & Todd, 1995b
Perceived Self-efficacy	SE1 (I think I have the personal ability required to use solar technology for farming). SE2 (I think I understand how solar technology for farming works. SE3 (I think I have the personal ability required to use biomass technology for farming). SE4 (I think I understand how biomass technology for farming works).	Ajzen, 1991; Sharifzadeh et al., 2017
Resource Facilitating Conditions	RFC1 Using solar energy will require ownership of plot(s) of land(s). RFC2 Using solar energy will require adequate money/funds. RFC3 (Using biomass energy will require crop/livestock residue) RFC4 (Using biomass energy will require money/funds).	Venkatesh et al., 2003
Technology Facilitating Conditions	TFC1 (To use solar technology, the spare parts to mend the equipment must be available). TFC2 (To use solar technology, technical experts/equipment repairers must be available). TFC3 (To use biomass technology, the spare parts to mend the equipment must be available). TFC4 (To use biomass technology, technical experts/equipment repairers must be available).	Venkatesh et al., 2003
Attitude	ATT1 (Solar technology is affordable compared to other energy technologies). ATT2 (Biomass technology is useful to me for farming). ATT3 (I will be comfortable operating solar technology alone). ATT4 (Using solar technology has minimal or no effect on my farm yields).	Ajzen, 1991; Fishbein & Ajzen, 1977
Subjective norm	SN1 (Other farmers similar to myself will approve the use of solar technology for farming). SN2 (Other farmers similar to myself will approve the use of biomass technology for farming). SN3 (Leaders of a farmer Cooperative/Association will approve the use of biomass technology for farming).	Ajzen, 1991; Fishbein & Ajzen, 1977

Table 2. *Cont.*

Perceived behavioural control	PBC1 (To use solar technology, it must be available in the market for adoption). PBC2 (Biomass energy has a relatively lower cost.) PBC3 (To use biomass technology, it must be available in the market for adoption).	Ajzen, 1991; Fishbein & Ajzen, 1977
Adoption Intention	AI1 (What is the likelihood that you will adopt solar energy for agriculture?) AI2 (What is the likelihood that you will adopt biomass energy for agriculture?)	Taylor & Todd, 1995b

4. Results

4.1. Socio-demographics

Most participants were male (79%) and had no formal education (64%), with only (22%) obtaining primary school education (Table 3). Although females represented the majority of the population in Lawra Municipality, male farmers formed the majority of the survey participants primarily because they represented household heads and owned the land on which farming was conducted. This reflects the culture of the Lawra traditional area and the larger Ghanaian society where inheritance is predominantly patrilinear such that males are more likely to inherit, or own land compared to females (Bonye, 2022; Vanderpuye et al., 2020). These existing socio-cultural practices have biased the participatory process, resulting in men dominating the research participants included.

Table 3. Summary of descriptive statistics of farmers' socio-demographic characteristics.

VARIABLES	MEAN	SD	
Age (years)	48.03	9.98	
Household size (number of people)	6.96	3.42	
Farm size (acres)	5.22	2.16	
Farmer experience (years)	16.85	10.20	
Farmer income (GHS-Ghana Cedis)	764.52	597.59	
Energy cost (GHS)	239.33	158.25	
VARIABLES	**CATEGORIES**	**FREQUENCY**	**PERCENTAGE (%)**
Gender	Male	329	78.7
	Female	89	21.3
Education	None	267	63.9
	To Primary school	91	21.8
	To Junior high school	42	10.0
	To Senior high school	12	2.9
	To Tertiary	6	1.4
Purpose of farming	Food/household consumption	410	98.1
	Income	5	1.2
	Traditional heritage	3	.7
Farm labour source	Extended family	131	31.3
	Hired labour	116	27.8
	Household	171	40.9

The average age of farmers was 48 years, and average farming experience was 17 years. On average, a farmer's household was comprised of 7 members with an average farm size of 5 acres (about 2 hectares). Household members contributed an average of 41% to farm labour. Other sources of farm labour included extended family members (31%) and hired labour (28%). Annually, the average cost of farm energy inputs was about GHS239.00 (USD19.14). The annual farm income of farmers was about GHS765.00 (USD61.26). About 98% of farmers primarily cultivated land to provide food for household consumption.

4.2. Constructs Reliability and Validity Analysis

A construct reliability analysis was performed to estimate the internal consistency of the items included in each construct. A composite reliability (CR) test was performed, where all the research constructs had values ranging from 0.807 to 0.978, which was greater than the acceptable value of 0.7 or higher (see Table 4; Anderson & Gerbing, 1988; Chen, 2016). Convergent and discriminant validity analyses were conducted (Chen, 2016; Hair et al., 2021). Using the average variance extracted (AVE), convergent validity was established, with all constructs reaching the acceptable value of > 0.5 (Fornell & Larcker, 1981; Naqshbandi et al., 2015). Discriminant validity was measured using the Fornell and Larcker (1981) principle, where the square root of AVE needs to be greater than the correspondence of an individual construct against other constructs (Hair et al., 1998; Kline, 2023). The results suggested discriminant validity was acceptable (Table 5).

Table 4. Reliability and Convergent Validity of Constructs.

Constructs	CR > 0.7	AVE > 0.5	MSV	ASV	Convergent Validity CR>AVE AVE>.5
Perceived Behavioural Control	0.927	0.810	0.420	0.186	YES
Perceived Ease of Use	0.931	0.820	0.235	0.025	YES
Perceived Usefulness	0.807	0.521	0.342	0.118	YES
Compatibility	0.867	0.623	0.334	0.082	YES
Risk	0.876	0.703	0.129	0.039	YES
Peer Influence	0.870	0.634	0.420	0.174	YES
External Influence	0.855	0.613	0.397	0.168	YES
Self-Efficacy	0.883	0.656	0.159	0.059	YES
Resource Facilitating Conditions	0.868	0.569	0.090	0.025	YES
Technology Facilitating Conditions	0.901	0.703	0.377	0.135	YES
Attitude	0.897	0.686	0.104	0.035	YES
Subjective Norms	0.886	0.722	0.335	0.109	YES
Adoption Intention	0.978	0.956	0.235	0.031	YES

Note: CR = Composite Reliability; AVE = Average Variance Extracted; MSV = Maximum Shared Squared Variance; ASV = Average Shared Squared Variance.

Table 5. Discriminant Validity Analysis of Constructs.

Perceived Behavioural Control	**Ease Of Use**	**Perceived Usefulness**	**Compatibility**	**Risk**	**Peer Influence**	**External Influence**	**Self-Efficacy**	**Resource Facilitating Conditions**	**Technology Facilitating Conditions**	**Attitude**	**Subjective Norms**	**Adoption Intention**	**Discriminant Validity MSV<AVE ASV<AVE**
0.900													YES
−0.064	**0.905**												YES
0.524	−0.027	**0.722**											YES
0.578	0.011	0.257	**0.790**										YES
0.204	0.031	0.233	−0.008	**0.838**									YES
0.648	−0.063	0.487	0.364	0.293	**0.796**								YES
0.611	−0.115	0.417	0.392	0.359	0.630	**0.783**							YES
0.287	−0.109	0.323	0.204	−0.040	0.399	0.345	**0.810**						YES
0.196	−0.139	0.074	0.179	0.077	0.135	0.238	0.078	**0.754**					YES
0.614	−0.014	0.585	0.306	0.241	0.584	0.439	0.177	0.127	**0.839**				YES
0.323	0.098	0.173	0.214	0.165	0.267	0.245	0.100	0.052	0.190	**0.828**			YES
0.421	−0.058	0.342	0.231	0.177	0.476	0.579	0.370	0.300	0.352	0.062	**0.850**		YES
0.077	0.485	−0.118	0.168	−0.169	−0.002	−0.113	−0.088	−0.084	−0.071	0.124	−0.100	**0.978**	YES

Note: Values in bold are the square roots of AVEs of relevant constructs in Table 4.

4.3. Measurement Model Evaluation

Structural Equation Modelling involving a two-step approach was conducted to test the research model. The maximum-likelihood approach was used to estimate the parameters of the model (measurement model evaluation; Hair et al., 1998). The evaluation of the goodness-of-fit indices to validate the research model against the data was conducted.

Three fit indices are needed to establish an acceptable model fit (Hair et al., 2003; Holmes-Smith et al., 2006; Zhou & Abdullah, 2017). To establish and report on an overall goodness-fit model, the absolute fit indices and comparative fit indices were used to evaluate the fitness of the research model. According to Byrne (2013), CMIN/DF, RMSEA, CFI, IFI, and TLI are sufficient to establish the overall goodness-fit model.

The initial measurement model evaluation generated the following indices CMIN/DF = 3.073, RMSEA = 0.71, CFI = .869, TLI = .852, and IFI = .870. (CMIN/DF and RMSEA) which met the recommended values (CFI, TLI, and IFI) but did not satisfy the goodness-of-fit criteria; hence, an overall model fit was not obtained. The model fit was improved by deleting items and correlating error terms as specified under the model's modification indices (MIs). According to Anderson and Gerbing (1988) and Lassoued (2014), connecting or deleting indicators can improve an unacceptable model fit. Improving a poor model fit (i.e., model re-specification) is required in SEM when the goodness-of-fit model indicators do not meet the acceptable threshold (Anderson & Gerbing, 1988; Bagozzi & Yi, 2012; Saris et al., 1987). As a result, the following items (PU3, CT1, PI1, PI4, EI1, SE1, SE2, RFC1, RFC4, and TFC1) were deleted from the model with the model modification indices of (>30). Consequently, an adequate and acceptable overall model fit was established CMIN/DF = 2.573, RMSEA = 0.61, CFI = 0.932, TLI = 0.918, and IFI = 0.933.

4.4. Structural Model Evaluation (Hypotheses Testing)

Given that the measurement model was evaluated, modified and yielded an overall good model fit, the structural model was evaluated, and the research hypotheses tested. From the hypothetical model, it is assumed that positive Attitude, positive Perceived Subjective Norms, and high Perceived Behavioural Control directly predict a farmer's Behavioural Intention to adopt renewable energy technology. It is further assumed that greater Perceived Ease of Use, greater Perceived Usefulness, greater Compatibility, higher Perceived Risk, higher Perceived Peer and External influence, higher Self-Efficacy, and greater Perceived Access to Resources and Technology Facilitating Conditions affect Attitude, Subjective Norms, and Perceived Behavioural Conditions. The goodness-of-fit indices were re-evaluated to ensure the model fit the data being used for the structural model evaluation and testing of the hypothesised relationships in the model. Overall, the goodness-of-fit indices reported satisfied the recommended values: CMIN/DF = 3.060, RMSEA = 0.70, CFI = 0.906, TLI = 0.900, and IFI = 0.907.

The results of the structural modelling showed that all the hypothesised relationships in the model were supported with the exception of Subjective Norms (see Table 6).

Table 6. Results of hypotheses testing.

Hypothesis	Regression Path	Coefficients (SRW)	P-value	Remarks
H1: A positive attitude will positively affect a farmer's intention to adopt a renewable energy technology for farming.	Attitude ---> Adoption Intention	.100	.055*	Supported
H2: Positive perceived subjective norms will positively affect a farmer's intention to adopt a renewable energy technology for farming.	Subjective Norms --->Adoption Intention	−.146	.007**	Not supported
H3: High perceived Behavioural Control will positively affect a farmer's intention to adopt a renewable energy technology for farming.	Perceived Behavioural Control ---> Adoption Intention	.096	.072*	Supported
H4: Greater perceived ease of use will positively affect a farmer's attitude to adopt renewable energy technology for farming.	Perceived ease of use ---> Attitude	.098	.056*	Supported
H5: Greater perceived usefulness will positively affect a farmer's attitude to adopt renewable energy technology for farming.	Perceived usefulness ---> Attitude	.102	.092*	Supported
H6: Greater perceived compatibility will positively affect a farmer's attitude to adopting renewable energy technology for farming.	Compatibility ---> Attitude	.217	0.01***	Supported
H7: Lower perceived risk will positively affect a farmer's attitude to adopt renewable energy technology for farming.	Risk ---> Attitude	.144	.008**	Supported
H8: Peer influence will affect a farmer's subjective norm to adopt renewable energy technology for farming.	Peer influence ---> Subjective Norms	.132	.013**	Supported
H9: External influence will affect a farmer's subjective norm to adopt renewable energy technology for farming.	External influence ---> Subjective Norms	.514	0.01***	Supported
H10: Higher perceived self-efficacy will positively affect a farmer's perceived behavioural control to adopt renewable energy technology for farming.	Self-efficacy ---> Perceived Behavioural Control	.230	0.01***	Supported
H11: Greater perceived access to resource-facilitating conditions will positively affect a farmer's perceived behavioural control to adopt renewable energy technology for farming.	Resource facilitating conditions ---> Perceived Behavioural Control	.149	0.01***	Supported
H12: Greater perceived access to technology-facilitating conditions will positively affect a farmer's perceived behavioural control to adopt renewable energy technology for farming.	Technology facilitating conditions ---> Perceived Behavioural Control	.534	0.01***	Supported

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ indicate statistical significance at 1%, 5%, and 10% respectively.
*Standardised Regression Weight – SRW

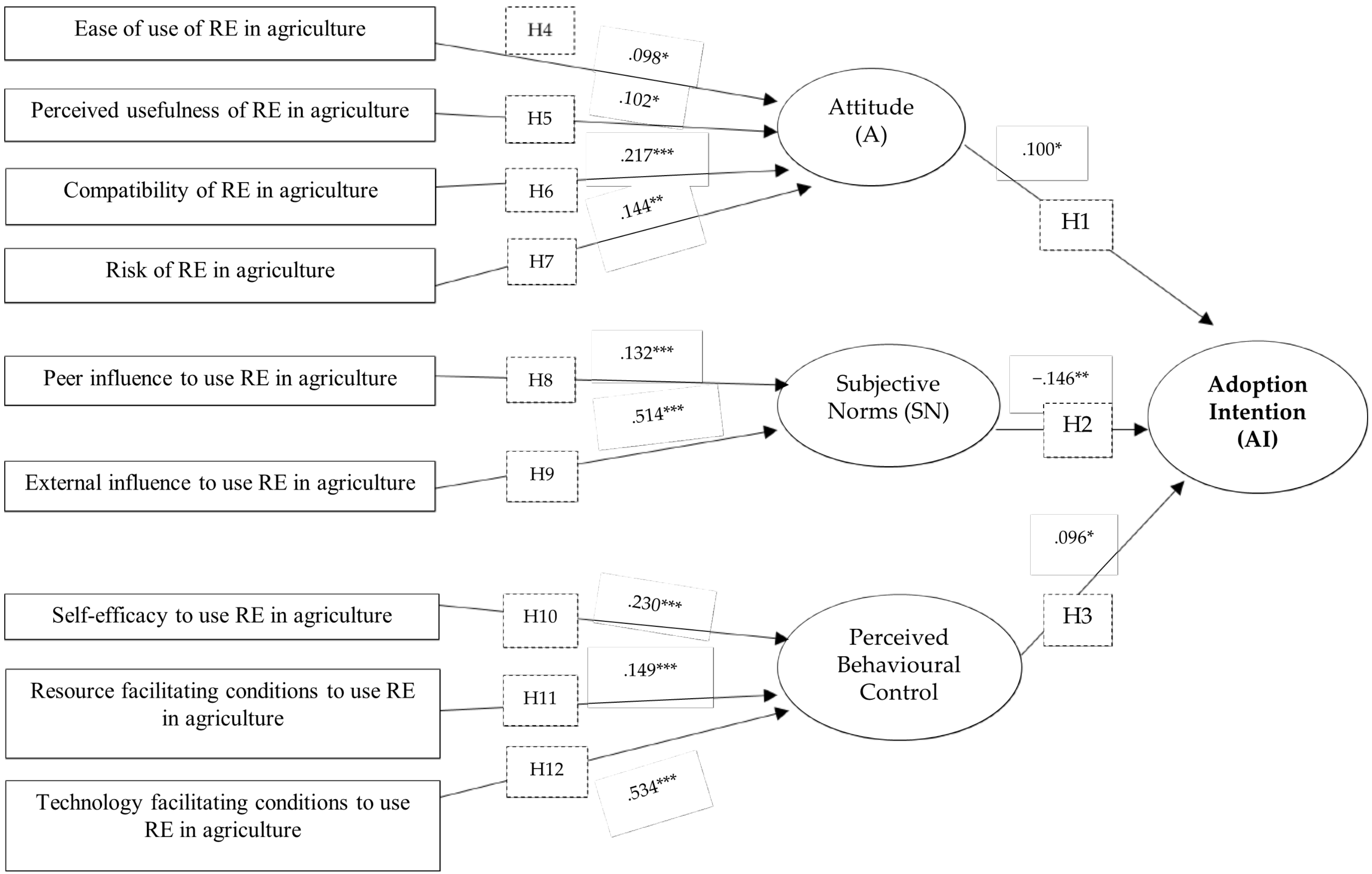


Figure 3. Results of structural regression path of the hypothesised model (DTPB).
Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ indicate statistical significance at 1%, 5%, and 10% respectively.

5. Discussion

The results showed that positive Attitude and high Perceived Behavioural Control positively and moderately affected farmers' intention to adopt renewable energy technology in their agronomic practices. Similarly, farmers perceived that if they had greater access to conditions for renewable energy technology, they were more likely to develop an intention to adopt renewable energy. These results are consistent with earlier research, which found that farmers' intention to adopt new technology was significantly influenced by a positive attitude towards the technology and perceived control over adoption (Bagheri et al., 2019; Borges et al., 2014; Bruijnis et al., 2013; Lalani et al., 2016; Rezaei et al., 2020; Tama et al., 2021; Yazdanpanah et al., 2014). At present, the use of renewable energy technology in farming is not widespread in Lawra Municipality (Karbo et al., 2022; Stock et al., 2023). However, these results suggest that if farmers have a positive attitude towards renewable energy technology, they are more likely to develop an intention to adopt it. Therefore, developing interventions that change farmers' attitudes to be more positive will increase the likelihood of them adopting renewable energy. This might be achieved, for example, through introducing renewable energy technology to farmers using learning platforms, including field demonstrations and trials to demonstrate the benefits of using the technology (Cheung & Vogel, 2013; Gebrezgabher et al., 2015; Rezaei et al., 2020; Zeweld et al., 2017a).

Subjective Norms did not positively influence farmers' intention to adopt renewable energy technology but rather had a negative relationship with behavioural intention. Similar research findings by (Bagheri et al., 2019; Elahi et al., 2022; Maleksaeidi & Keshavarz, 2019; Tama et al., 2021) found a negative relationship between subjective norms and farmers' behavioural intention to adopt agricultural technologies. Further, this finding is consistent with previous research that reported that perceived subjective norms did not positively influence individuals' adoption intention due to social factors such as cultural differences and perceived bias in relation to technology (Bagheri et al., 2021; Buyinza et al., 2020; Laksono et al., 2022; Tan et al., 2017). It is also possible that few farmers in the study area were adopting renewable energy technology for farming when the research was conducted, creating a normative social environment in relation to the non-adoption of renewable energy, and so had a negative association with behavioural intention. If in the future it is the case that where more farmers adopt renewable energy for farming, peer-to-peer learning may be leveraged leading to a normative social environment that will positively affect farmers' behavioural intention to adopt renewable energy technology (Devi et al., 2020; Nyambo et al., 2022).

As predicted by the model, greater Perceived Compatibility and lower Perceived Risk had significant positive effects on farmers' attitudes to adopt renewable energy technology. The results are consistent with those of Dixit et al. (2023) and Rezaei et al. (2020), which suggested that farmers adopt innovative technologies compatible with their contextual and pragmatic situations. For example, farmers in Lawra Municipality are more likely to adopt renewable energy technologies (e.g., solar energy to power water pumps to irrigate crops). In Lawra Municipality, farmers are economically dependent primarily on agriculture. As a consequence, they are less likely to adopt technologies which pose a risk to their only source of income, and which potentially have minimal or no risk to their agricultural productivity. Greater Perceived Ease of Use and greater Perceived Usefulness had positive but moderate effects on farmers' attitudes to adopt renewable energy technology. Farmers' perceptions of the ease of use and usefulness of renewable energy technologies may depend on farmers' level of experience or information they have acquired about the technology. Therefore, when farmers obtain sufficient information about how to use a renewable energy technology, and the extent to which it is useful, they will indicate greater intentions to adopt it. Perceived Ease of Use and Usefulness has also been shown to positively influence farmers' adoption behaviour of agricultural innovations (Dixit et al., 2023; Kardooni et al., 2016; Li et al., 2021; Ulhaq et al., 2022).

A positive effect of peer and external influences on farmers' subjective norms associated with adopting renewable energy technology was observed. Adesina and Chianu (2002); Li et al. (2020); Wang et al. (2019) reported that peer and external influences affected farmers' adoption of agricultural innovations (the construct of subjective norms). As agricultural extension agents are influential in relation to developing a Subjective Norm which favours adoption, the government could ensure sufficient resources are allocated to agricultural extension activities focused on promoting the adoption of renewable energy technology and other innovations which will help the agriculture sector attain Net Zero targets. This in turn will positively influence behavioural intention. Peer Influence also influences Subjective Norms. The former is likely to become more positive as more farmers adopt renewable energy and this Subjective Norm would be indirectly influenced by extension service and other knowledge exchange activities associated with the promotion of renewable energy in agriculture which in turn would influence behavioural intention.

Positive effects of perceived high Self-Efficacy, greater perceived Access to Resource Facilitating Conditions, and greater perceived Access to Technology Facilitating Conditions were observed in relation to the Perceived Behavioural Control of farmers to adopt renewable energy.

Yazdanpanah et al. (2022) reported that greater perceived Self-Efficacy increased farmers' intention to adopt new technologies. Higher perceived Self-Efficacy implies that farmers perceive themselves as having a greater ability to adopt renewable energy technology without at the same time perceiving difficulty in doing this. Therefore, higher perceived Self-Efficacy on the part of farmers should lead to a greater perception of Perceived Behavioural Control over their adoption of renewable energy technology for farming. In addition, farmers are more likely to develop an intention to adopt renewable energy technology when they believe resources such as land and financial support are readily accessible. Again, extension workers may be instrumental in identifying training requirements to provide the knowledge required to adopt renewable energy which addresses the issue of perceived Self-Efficacy, especially if this is coupled with policies which promote (e.g. infrastructure requirements, subsidy programmes and technology support) in relation to renewable technology adoption. For example, there is evidence that the adoption of renewable energy by farmers is contingent on the technology and spare parts being both available and accessible to end-users. For example, Faridi et al. (2020) and Oliveira et al. (2014) reported that perceptions of facilitating conditions determined farmers' behavioural intention to adopt new technologies.

5.1. Theoretical and Practical Implications

This research extends the application of the Decomposed Theory of Planned Behaviour to predict farmers' adoption behaviour in relation to renewable energy technology in Northern Ghana, within an LMIC country demonstrating that the Decomposed Theory of Planned Behaviour can potentially be used in future research can be applied to predict and explain farmers' technology adoption behaviours.

The Decomposed Theory of Planned Behaviour integrates constructs from the Technology Acceptance Model, the Theory of Planned Behaviour, and the Diffusion of Innovation Theory (Taylor & Todd, 1995a). In this research, a perceived risk variable from Expected Utility Theory was added to the model. Perception of lower risk was a significant predictor of farmers' adoption behaviour. Future research may need to consider a wide range of variables or factors that can be integrated into the Decomposed Theory of Planned Behaviour to explain farmers' adoption behaviour.

The Decomposed Theory of Planned Behaviour assumes that Subjective Norm influences an adoption behaviour, which could be positive or negative. While Subjective Norms have also been reported to increase the adoption intention of farmers (Elahi et al., 2022; Maleksaeidi & Keshavarz, 2019; Tama et al., 2021), these results suggest an understanding of the social environment in which social pressures are generated that potentially affect farmers' adoption behaviour is needed, including within the context of the Decomposed Theory of Planned Behaviour in relation to understanding farmers' adoption behaviour.

5.2. Limitations

A major limitation of this research was its focus on investigating farmers' intention to adopt renewable energy technology rather than the adoption behaviour itself. At the time of conducting the research, renewable energy technology for farming was not widespread in Ghana with solar and biomass energy technology being the most likely adopted renewable energy forms by farmers. Future research might investigate how behavioural intention relates to the technology's actual adoption. Various forms of renewable energy, including solar, biomass, hydro, and wind-based technologies, can support agricultural activities. This research limited the focus of renewable energy technology to solar and biomass technologies because these prominent forms of renewable energy are being promoted to Ghanaian farmers for application within the agricultural sector.

A second, and important, limitation was the sampling approach, which was skewed towards the inclusion of more male participants. While females constitute the majority of the population in Lawra Municipality, male farmers (79%) formed the majority of the survey participants primarily because they represented household heads and owned the land on which farming was conducted. However, the results may exclude the perspective of women in the context of farming and renewable energy adoption in Northern Ghana. Future research may expand the inclusion criteria for participants beyond the household to capture more female farmers who often are not household heads and do not own farmlands but contribute significantly to performing farm activities.

5.3. Recommendations

Policymakers could consider farmers' psychological characteristics when formulating policies and interventions to promote the adoption of renewable energy technology. Such policies and interventions that align with farmers' psychological attributes can enhance farmers' perception of renewable energy technology and consequently increase the likelihood of their adopting it.

Agricultural policy development should not be informed only by economic factors but must also address psychological factors determining adoption.

Policies to provide achievable targets and clear roadmaps in relation to developing and facilitating the adoption of renewable energy technology by farmers and other actors in the agricultural value chain are needed. This implies that governments could establish pragmatic policy regimes, including tax and credit subsidies and green financing frameworks to increase support for farmers to adopt renewable energy technology (Balana & Oyeyemi, 2020; Taghizadeh-Hesary & Yoshino, 2020). Technology innovators and designers should consider farmers' psychological factors when developing renewable energy technology potentially resulting in the development of wide-ranging renewable energy technology to align the farming needs of different farmers.

6. Conclusions

Renewable energy can contribute to reducing carbon emissions and achieving more sustainable agriculture practices. To increase adoption in agriculture, factors determining farmers' adoption need to be understood. In line with this, a theoretical model was applied in this research to understand predictors of farmers' adoption of renewable energy technology for farming. The Decomposed Theory of Planned Behaviour predicts behavioural intention based on three main psychological constructs, Attitude, Subjective Norms, and Perceived Behavioural Control, which are affected by sub-constructs. From the model, it was concluded that farmers' behavioural intention to adopt renewable energy was influenced by Attitude and high Perceived Behavioural Control. In addition, farmers' Attitude towards renewable energy adoption was affected by greater perceived Ease of Use, greater Perceived Usefulness, higher Perceived Risk, and greater Perceived Compatibility. Although farmers' Subjective Norms did not positively influence behavioural intention to adopt renewable energy, farmers' subjective norms towards renewable energy were affected by Peer and External Influences. Further, farmers Perceived Behavioural Control towards renewable energy adoption was determined by high perceived Self-Efficacy, greater perceived Access to Resource Facilitating Conditions, and Technology Facilitating Conditions. The findings of the research contribute to our understanding of farmers' intention to adopt renewable energy for farming, as well as providing evidence for policy and extension activities which may promote the adoption of renewable energy in Ghanaian agriculture.

CRediT Author Statement: Ransford Teng-viel Karbo: Conceptualisation, Methodology, Data collection, Data curation, Formal analysis, Writing – original draft, and Writing – review and editing; **Lynn J. Frewer:** Conceptualisation, Methodology, Supervision, and Writing – review and editing; **Francisco J. Areal:** Conceptualisation, Methodology, Supervision, and Writing – review and editing; **Albert Boaitey:** Conceptualisation, Methodology, Supervision, and Writing – review and editing; **Glyn Jones:** Conceptualisation, Methodology, Supervision, and Writing – review and editing; **Guy Garrod:** Writing – review and editing.

Data Availability Statement: Data will be made available on request.

Funding: This research was funded by the Ghana Education Trust Fund (GETFUND).

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgement: Not applicable.

References

Abaka, J. U., Olokede, O., Ibraheem, T. B, Salman, H., & Fabiyi, O. (2017). Renewable energy and agriculture: A partnership for sustainable development. *International Journal of Modern Engineering Research*, *7*(5), 39−44. https://mail.ijmer.com/papers/Vol7_issue5/Version-2/F7523944.pdf

Adams, S., & Nsiah, C. (2019). Reducing carbon dioxide emissions; Does renewable energy matter? *Science of The Total Environment*, *693*, 133288. https://doi.org/10.1016/j.scitotenv.2019.07.094

Adesina, A. A., & Chianu, J. (2002). Determinants of farmers' adoption and adaptation of alley farming technology in Nigeria. *Agroforestry Systems*, *55*, 99−112. https://doi.org/10.1023/A:1020556132073

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179−211. https://doi.org/10.1016/0749-5978(91)90020-T

Ali, S. M., Dash, N., & Pradhan, A. (2012). Role of renewable energy on agriculture. *International Journal of Engineering Sciences & Emerging Technologies*, *4*(1), 51−57. https://www.ijeset.com/media/0001/6N7-IJESET711.pdf

Alomary, A., & Woollard, J. (2015, November 21). How is technology accepted by users? A review of technology acceptance models and theories. The IRES 17th International Conference, London, United Kingdom. https://eprints.soton.ac.uk/382037/1/110-14486008271-4.pdf

Ambali, O. I., Areal, F. J., & Georgantzis, N. (2021). On spatially dependent risk preferences: The case of Nigerian farmers. *Sustainability*, *13*(11), 5943. https://www.mdpi.com/2071-1050/13/11/5943

Anderson, J. C., & Gerbing, D. W. (1988). Structural equation modeling in practice: A review and recommended two-step approach. *Psychological Bulletin*, *103*(3), 411−423. https://doi.org/10.1037/0033-2909.103.3.411

Aryal, J. P., Rahut, D. B., Thapa, G., & Simtowe, F. (2021). Mechanisation of small-scale farms in South Asia: Empirical evidence derived from farm households survey. *Technology in Society*, *65*, 101591. https://doi.org/10.1016/j.techsoc.2021.101591

Asiamah, T. A., Tettey, G., Boyetey, D. B., & Djimajor, R. T. (2023). Examining awareness and usage of renewable energy technologies in non-electrified farming communities in the Eastern Region of Ghana. In C. Aigbavboa, J. N. Mojekwu, W. D. Thwala, L. Atepor, E. Adinyira, G. Nani, & E. Bamfo-Agyei (Eds.), *Sustainable Education and Development – Sustainable Industrialization and Innovation* (pp. 14–27). Springer Cham. https://doi.org/10.1007/978-3-031-25998-2_2

Awuni, J. A., Azumah, S. B., & Donkoh, S. A. (2018). Drivers of adoption intensity of improved agricultural technologies among rice farmers: evidence from northern Ghana. *Review of Agricultural and Applied Economics (RAAE)*, *21*(2), 48–57. https://roaae.org/wp-content/uploads/2018/11/RAAE_2_2018_Awuni_et_al.pdf

Ayamga, E. A., Kemausuor, F., & Addo, A. (2015). Technical analysis of crop residue biomass energy in an agricultural region of Ghana. *Resources, Conservation and Recycling*, *96*, 51−60. https://doi.org/10.1016/j.resconrec.2015.01.007

Bagheri, A., Allahyari, M. S., & Ashouri, D. (2016). Interpretation on biological control adoption of the rice stem borer, Chilo suppressalis (Walker) in North Part of Iran: Application for Technology Acceptance Model (TAM). *Egyptian Journal of Biological Pest Control*, *26*(1), 27−33. https://www.researchgate.net/publication/301230914

Bagheri, A., Bondori, A., Allahyari, M. S., & Damalas, C. A. (2019). Modeling farmers' intention to use pesticides: An expanded version of the theory of planned behavior. *Journal of Environmental Management*, *248*, 109291. https://doi.org/10.1016/j.jenvman.2019.109291

Bagheri, A., Emami, N., & Damalas, C. A. (2021). Farmers' behavior towards safe pesticide handling: An analysis with the theory of planned behavior. *Science of The Total Environment*, *751*, 141709. https://doi.org/10.1016/j.scitotenv.2020.141709

Bagozzi, R. P., & Yi, Y. (2012). Specification, evaluation, and interpretation of structural equation models. *Journal of the Academy of Marketing Science*, *40*, 8−34. https://doi.org/10.1007/s11747-011-0278-x

Bala, I., & El-jajah, W. G. (2019). Relationship between promotion and classroom teachers' job satisfaction in Senior Secondary Schools in Taraba State, Nigeria. *International Journal of Philosophy and Social-Psychological Sciences*, *5*(3), 63–67. https://sciarena.com/storage/models/article/QkqTpqGfngW0U0pIxTmwO9LoLxcdn4VqzepuUn2dJqwlfo5dWuoJr2xlGN9R/relationship-between-promotion-and-classroom-teachers-job-satisfaction-in-senior-secondary-schools.pdf

Balana, B., & Oyeyemi, M. (2020). *Credit constraints and agricultural technology adoption: Evidence from Nigeria*. International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.133937

Bayrakcı, A. G., & Koçar, G. (2012). Utilization of renewable energies in Turkey's agriculture. *Renewable and Sustainable Energy Reviews*, *16*(1), 618–633. https://doi.org/10.1016/j.rser.2011.08.027

Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J. P., & Smith, P. (2013). Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biology*, *19*(1), 3–18. https://doi.org/10.1111/j.1365-2486.2012.02786.x

Bell, M. J., Cloy, J. M., & Rees, R. M. (2014). The true extent of agriculture's contribution to national greenhouse gas emissions. *Environmental Science & Policy*, *39*, 1–12. https://doi.org/10.1016/j.envsci.2014.02.001

Best, S. (2014). *Growing power: Exploring energy needs in smallholder agriculture*. International Institute for Environment and Development (IIED). https://www.iied.org/16562iied

Blandford, D., & Hassapoyannes, K. (2018). *The role of agriculture in global GHG mitigation*. Organisation for Economic Co-operation and Development (OECD). https://doi.org/10.1787/da017ae2-en

Bollen, K. A., & Noble, M. D. (2011). Structural equation models and the quantification of behavior. *Proceedings of the National Academy of Sciences*, *108*(supplement_3), 15639–15646. https://doi.org/10.1073/pnas.1010661108

Bonye, S. Z. (2022). Can i own land in my matrimonial home? A gender analysis of access to and ownership of agricultural land in Northern Ghana, Ghana. *GeoJournal*, *87*, 2685–2697. https://doi.org/10.1007/s10708-021-10396-4

Borges, J. A. R., Foletto, L., & Xavier, V. T. (2015). An interdisciplinary framework to study farmers decisions on adoption of innovation: Insights from Expected Utility Theory and Theory of Planned Behavior. *African Journal of Agricultural Research*, *10*(29), 2814–2825. https://doi.org/10.5897/AJAR2015.9650

Borges, J. A. R., Oude Lansink, A. G. J. M., Ribeiro, C. M., & Lutke, V. (2014). Understanding farmers' intention to adopt improved natural grassland using the theory of planned behavior. *Livestock Science*, *169*, 163–174. https://doi.org/10.1016/j.livsci.2014.09.014

Bruijnis, M., Hogeveen, H., Garforth, C., & Stassen, E. (2013). Dairy farmers' attitudes and intentions towards improving dairy cow foot health. *Livestock Science*, *155*(1), 103–113. https://doi.org/10.1016/j.livsci.2013.04.005

Buyinza, J., Nuberg, I. K., Muthuri, C. W., & Denton, M. D. (2020). Psychological factors influencing farmers' intention to adopt agroforestry: A structural equation modeling approach. *Journal of Sustainable Forestry*, *39*(8), 854–865. https://doi.org/10.1080/10549811.2020.1738948

Byrne, B. M. (2013). *Structural equation modeling with Mplus: Basic concepts, applications, and programming* (1st ed.). Routledge. https://doi.org/10.4324/9780203807644

Castillo, J. J. (2009). *Systematic sampling*. Retrieved March, 6, 2013, from http://www.scribd.com/doc/54018519/Systematic-sampling

Chel, A., & Kaushik, G. (2011). Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development*, *31*, 91–118. https://doi.org/10.1051/agro/2010029

Chen, M.-F. (2016). Extending the theory of planned behavior model to explain people's energy savings and carbon reduction behavioral intentions to mitigate climate change in Taiwan–moral obligation matters. *Journal of Cleaner Production*, *112*, 1746–1753. https://doi.org/10.1016/j.jclepro.2015.07.043

Cheteni, P., Mushunje, A., & Taruvinga, A. (2014). Barriers and incentives to potential adoption of biofuels crops by smallholder farmers in the Eastern Cape Province, South Africa. Munich Personal RePEc Archive. https://mpra.ub.uni-muenchen.de/59029/1/MPRA_paper_59029.pdf

Cheung, R., & Vogel, D. (2013). Predicting user acceptance of collaborative technologies: An extension of the technology acceptance model for e-learning. *Computers & Education*, *63*, 160–175. https://doi.org/10.1016/j.compedu.2012.12.003

Chin, W. W. (1998). Commentary: Issues and opinion on structural equation modeling. MIS Quarterly, *22*(1), vii-xvi. https://www.jstor.org/stable/249674

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, *13*(3), 319–340. https://doi.org/10.2307/249008

Devi, S. H. L., Kirbrandoko, Ujang, S., & Noor, Y. L. (2020). Factors encouraging the use of peer-to-peer lending by farmers. *Russian Journal of Agricultural and Socio-Economic Sciences*, *103*(7), 72–81. https://doi.org/10.18551/rjoas.2020-07.10

Dixit, K., Aashish, K., & Dwivedi, A. K. (2023). Antecedents of smart farming adoption to mitigate the digital divide – extended innovation diffusion model. *Technology in Society*, *75*, 102348. https://doi.org/10.1016/j.techsoc.2023.102348
Dulal, H. B., Shah, K. U., Sapkota, C., Uma, G., & Kandel, B. R. (2013). Renewable energy diffusion in Asia: Can it happen without government support? *Energy Policy*, *59*, 301–311. https://doi.org/10.1016/j.enpol.2013.03.040
Elahi, E., Khalid, Z., & Zhang, Z. (2022). Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture. *Applied Energy*, *309*, 118459. https://doi.org/10.1016/j.apenergy.2021.118459
Elsayir, H. A. (2014). Comparison of precision of systematic sampling with some other probability samplings. *American Journal of Theoretical and Applied Statistics*, *3*(4), 111–116. https://doi.org/10.11648/j.ajtas.20140304.16
Fami, H. S., Ghasemi, J., Malekipoor, R., Rashidi, P., Nazari, S., & Mirzaee, A. (2010). Renewable energy use in smallholder farming systems: A case study in Tafresh Township of Iran. *Sustainability*, *2*(3), 702–716. https://doi.org/10.3390/su2030702
Faridi, A. A., Kavoosi-Kalashami, M., & Bilali, H. E. (2020). Attitude components affecting adoption of soil and water conservation measures by paddy farmers in Rasht County, Northern Iran. *Land Use Policy*, *99*, 104885. https://doi.org/10.1016/j.landusepol.2020.104885
Fishbein, M., & Ajzen, I. (1977). Belief, attitude, intention, and behavior: An introduction to theory and research. *Philosophy and Rhetoric*, *10*(2), 130–132.
Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research*, *18*(1), 39–50. https://doi.org/10.1177/002224378101800104
Gebrezgabher, S. A., Meuwissen, M. P. M., Kruseman, G., Lakner, D., & Oude Lansink, A. G. J. M. (2015). Factors influencing adoption of manure separation technology in the Netherlands. *Journal of Environmental Management*, *150*, 1–8. https://doi.org/10.1016/j.jenvman.2014.10.029
Gunarathne, P. K. K. S., Wikramasuriya, H. V. A., Jayathilaka, M. W. A. P., & Wijesuriya, W. (2021). Behavioural factors affecting the adoption of manuring of smallholder mature rubber cultivations in Moneragala district. *Journal of the Rubber Research Institute of Sri Lanka*, *101*, 36–48. https://doi.org/10.4038/jrrisl.v101i0.1904
Hair, J. F., Bush, R. P., & Ortinau, D. J. (2003). *Marketing research: Within a changing information environment* (3rd ed.). McGraw-Hill/Irwin.
Hair, J. F., Anderson, R., Tatham, R., & Black, W. (1998). *Multivariate data analysis* (7th ed.). Prentice Hall.
Hair, J. F., Jr., Hult, G. T. M., Ringle, C. M., Sarstedt, M., Danks, N. P., & Ray, S. (2021). An introduction to structural equation modeling. In *Partial least squares structural equation modeling (PLS-SEM) using R* (pp. 1–29). Springer, Cham. https://doi.org/10.1007/978-3-030-80519-7_1
Harvey, M., & Pilgrim, S. (2011). The new competition for land: Food, energy, and climate change. *Food Policy*, *36*(supplement 1), S40–S51. https://doi.org/10.1016/j.foodpol.2010.11.009
Holmes-Smith, P., Coote, L., & Cunningham, E. (2006). *Structural equation modeling: From the fundamentals to advanced topics*. School Research, Evaluation and Measurement Services.
Hoyle, R. H. (2000). Confirmatory factor analysis. In H. E. A. Tinsley & S. D. Brown (Eds.), *Handbook of applied multivariate statistics and mathematical modeling* (pp. 465–497). Elsevier. https://doi.org/10.1016/B978-012691360-6/50017-3
Jebli, M. B., & Youssef, S. B. (2017). The role of renewable energy and agriculture in reducing CO_2 emissions: Evidence for North Africa countries. *Ecological Indicators*, *74*, 295–301. https://doi.org/10.1016/j.ecolind.2016.11.032
Jin, T., & Kim, J. (2018). What is better for mitigating carbon emissions – Renewable energy or nuclear energy? A panel data analysis. *Renewable and Sustainable Energy Reviews*, *91*, 464–471. https://doi.org/10.1016/j.rser.2018.04.022
Kabwe, G., Bigsby, H., & Cullen, R. (2009, August 27–28). Factors influencing adoption of agroforestry among smallholder farmers in Zambia. 2009 NZARES Conference, Nelson, New Zealand. https://hdl.handle.net/10182/3425
Kalanzi, F., Kyazze, F. B., Isubikalu, P., Kiyingi, I., Orikiriza, L. J. B., Okia, C., & Guuroh, R. T. (2021). Influence of socio-technological factors on smallholder farmers' choices of agroforestry technologies in the eastern highlands of Uganda. *Small-scale Forestry*, *20*, 605–626. https://doi.org/10.1007/s11842-021-09483-8
Karbo, R. T., Frewer, L. J., Areal, F., & Yu, E. (2022). Using renewable energy to meet the energy needs of smallholder farmers: Are there policies to promote adoption in Ghana? *Ghana Journal of Agricultural Science*, *57*(1), 15–29. https://doi.org/10.4314/gjas.v57i1.2
Kardooni, R., Yusoff, S. B., & Kari, F. B. (2016). Renewable energy technology acceptance in Peninsular Malaysia. *Energy Policy*, *88*, 1–10. https://doi.org/10.1016/j.enpol.2015.10.005
Khan, M. T. I., Ali, Q., & Ashfaq, M. (2018). The nexus between greenhouse gas emission, electricity production, renewable energy and agriculture in Pakistan. *Renewable Energy*, *118*, 437–451. https://doi.org/10.1016/j.renene.2017.11.043
Kline, R. B. (2023). *Principles and practice of structural equation modeling*. Guilford Publications.
Laksono, P., Irham, Mulyo, J. H., & Suryantini, A. (2022). Farmers' willingness to adopt geographical indication practice in Indonesia: A psycho behavioral analysis. *Heliyon*, *8*(8), Article e10178. https://doi.org/10.1016/j.heliyon.2022.e10178
Lalani, B., Dorward, P., Holloway, G., & Wauters, E. (2016). Smallholder farmers' motivations for using Conservation Agriculture and the roles of yield, labour and soil fertility in decision making. *Agricultural Systems*, *146*, 80–90. https://doi.org/10.1016/j.agsy.2016.04.002
Lassoued, R. (2014). How trust in the food system and in brands builds consumer confidence in credence attributes: A Structural Equation Model [Doctoral dissertation, University of Saskatchewan]. https://harvest.usask.ca/server/api/core/bitstreams/f3719cbe-c42f-474f-a68d-80ac44b61355/content
Lawal, A. I. (2023). The nexus between economic growth, energy consumption, agricultural output, and CO_2 in Africa: Evidence from frequency domain estimates. *Energies*, *16*(3), 1239. https://doi.org/10.3390/en16031239
Lawra Municipal Assembly. (2018). *Municipal medium term development plan 2018–2021*.
Lenka, S., Lenka, N. K., Sejian, V., & Mohanty, M. (2015). Contribution of agriculture sector to climate change. In V. Sejian, J. Gauhan, L. Baumgard, & C. Prasad (Eds.), *Climate change impact on livestock: Adaptation and mitigation* (pp. 37–48). Springer New Delhi. https://doi.org/10.1007/978-81-322-2265-1_3
Li, B., Ding, J., Wang, J., Zhang, B., & Zhang, L. (2021). Key factors affecting the adoption willingness, behavior, and willingness-behavior consistency of farmers regarding photovoltaic agriculture in China. *Energy policy*, *149*, 112101. https://doi.org/10.1016/j.enpol.2020.112101

Li, J., Feng, S., Luo, T., & Guan, Z. (2020). What drives the adoption of sustainable production technology? Evidence from the large scale farming sector in East China. *Journal of Cleaner Production*, *257*, 120611. https://doi.org/10.1016/j.jclepro.2020.120611

Liu, X., Zhang, S., & Bae, J. (2017a). The impact of renewable energy and agriculture on carbon dioxide emissions: Investigating the environmental Kuznets curve in four selected ASEAN countries. *Journal of Cleaner Production*, *164*, 1239–1247. https://doi.org/10.1016/j.jclepro.2017.07.086

Liu, X., Zhang, S., & Bae, J. (2017b). The nexus of renewable energy-agriculture-environment in BRICS. *Applied Energy*, *204*, 489–496. https://doi.org/10.1016/j.apenergy.2017.07.077

Makate, C. (2020). Local institutions and indigenous knowledge in adoption and scaling of climate-smart agricultural innovations among sub-Saharan smallholder farmers. *International Journal of Climate Change Strategies and Management*, *12*(2), 270–287. https://doi.org/10.1108/ijccsm-07-2018-0055

Maleksaeidi, H., & Keshavarz, M. (2019). What influences farmers' intentions to conserve on-farm biodiversity? An application of the theory of planned behavior in fars province, Iran. *Global Ecology and Conservation*, *20*, Article e00698. https://doi.org/10.1016/j.gecco.2019.e00698

Mapemba, L. D., Grevulo, J. A., & Mulagha, A. M. (2013). What drives adoption of biofuel (*Jatropha Curcas*) production in central eastern Malawi? *Journal of Energy Technologies & Policy*, *3*(10), 39–45. https://core.ac.uk/download/pdf/234667461.pdf

Martinho, V. J. P. D. (2018). Interrelationships between renewable energy and agricultural economics: An overview. *Energy Strategy Reviews*, *22*, 396–409. https://doi.org/10.1016/j.esr.2018.11.002

Meijer, S. S., Catacutan, D., Ajayi, O. C., Sileshi, G. W., & Nieuwenhuis, M. (2015). The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *International Journal of Agricultural Sustainability*, *13*(1), 40–54. https://doi.org/10.1080/14735903.2014.912493

Mogaka, V., Ehrensperger, A., Iiyama, M., Birtel, M., Heim, E., & Gmuender, S. (2014). Understanding the underlying mechanisms of recent *Jatropha curcas* L. adoption by smallholders in Kenya: A rural livelihood assessment in Bondo, Kibwezi, and Kwale districts. *Energy for Sustainable Development*, *18*, 9–15. https://doi.org/10.1016/j.esd.2013.11.010

Mongin, P., & Baccelli, J. (2021). Expected utility theory, Jeffrey's decision theory, and the paradoxes. *Synthese*, *199*, 695–713. https://doi.org/10.1007/s11229-020-02691-3

Mukherji, A., Chowdhury, D. R., Fishman, R., Lamichhane, N., Khadgi, V., & Bajracharya, S. (2017). *Sustainable financial solutions for the adoption of solar powered irrigation pumps in Nepal's Terai*. International Centre for Integrated Mountain Development. https://doi.org/10.53055/ICIMOD.695

Musungwini, S., van Zyl, I., & Kroeze, J. H. (2022). The perceptions of smallholder farmers on the use of mobile technology: A naturalistic inquiry in Zimbabwe. In K. Aria (Ed.), *Advances in Information and Communication: Proceedings of the 2022 Future of Information and Communication Conference (FICC), Volume 2* (pp. 530–544). Springer Cham. https://doi.org/10.1007/978-3-030-98015-3_37

Musyoki, M. E., Busienei, J. R., Gathiaka, J. K., & Karuku, G. N. (2022). Linking farmers' risk attitudes, livelihood diversification and adoption of climate smart agriculture technologies in the Nyando basin, South-Western Kenya. *Heliyon*, *8*(4), Article e09305. https://doi.org/10.1016/j.heliyon.2022.e09305

Mwakaje, A. G. (2008). Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. *Renewable and Sustainable Energy Reviews*, *12*(8), 2240–2252. https://doi.org/10.1016/j.rser.2007.04.013

Naqshbandi, M. M., Kaur, S., & Ma, P. (2015). What organizational culture types enable and retard open innovation? *Quality & Quantity*, *49*, 2123–2144. https://doi.org/10.1007/s11135-014-0097-5

Nguyen, N., & Drakou, E. G. (2021). Farmers intention to adopt sustainable agriculture hinges on climate awareness: The case of Vietnamese coffee. *Journal of Cleaner Production*, *303*, 126828. https://doi.org/10.1016/j.jclepro.2021.126828

Nyairo, N. M., Pfeiffer, L., Spaulding, A., & Russell, M. (2022). Farmers' attitudes and perceptions of adoption of agricultural innovations in Kenya: A mixed methods analysis. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *123*(1), 147–160. https://doi.org/10.17170/kobra-202204216055

Nyambo, D. G., Luhanga, E. T., Yonah, Z. O., Mujibi, F. D., & Clemen, T. (2022). Leveraging peer-to-peer farmer learning to facilitate better strategies in smallholder dairy husbandry. *Adaptive Behavior*, *30*(1), 51–62. https://doi.org/10.1177/1059712320971369

Nyamwena-Mukonza, C. (2012). Adoption of biofuels technologies by smallholder farmers in Zimbabwe. https://www.redesist.ie.ufrj.br/ga2012/paper/ChipoMukonza.pdf

Nyasulu, C., & Dominic Chawinga, W. (2019). Using the decomposed theory of planned behaviour to understand university students' adoption of WhatsApp in learning. *E-Learning and Digital Media*, *16*(5), 413–429. https://doi.org/10.1177/2042753019835906

Obiero, K. O., Waidbacher, H., Nyawanda, B. O., Munguti, J. M., Manyala, J. O., & Kaunda-Arara, B. (2019). Predicting uptake of aqua-culture technologies among smallholder fish farmers in Kenya. *Aquaculture International*, *27*, 1689–1707. https://doi.org/10.1007/s10499-019-00423-0

Oliveira, T., Faria, M., Thomas, M. A., & Popovič, A. (2014). Extending the understanding of mobile banking adoption: When UTAUT meets TTF and ITM. *International Journal of Information Management*, *34*(5), 689–703. https://doi.org/10.1016/j.ijinfomgt.2014.06.004

Olumba, C. N., Garrod, G., & Areal, F. J. (2024). Time preferences, land tenure security, and the adoption of sustainable land management practices in Southeast Nigeria. *Sustainability*, *16*(5), 1747. https://doi.org/10.3390/su16051747

Omulo, G., Daum, T., Köller, K., & Birner, R. (2024). Unpacking the behavioral intentions of 'emergent farmers' towards mechanized conservation agriculture in Zambia. *Land Use Policy*, *136*, 106979. https://doi.org/10.1016/j.landusepol.2023.106979

Opsomer, J. D., Francisco-Fernández, M., & Li, X. (2012). Model-based non-parametric variance estimation for systematic sampling. *Scandinavian Journal of Statistics*, *39*(3), 528–542. https://doi.org/10.1111/j.1467-9469.2011.00773.x

Pestisha, A., Gabnai, Z., Chalgynbayeva, A., Lengyel, P., & Bai, A. (2023). On-farm renewable energy systems: A systematic review. *Energies*, *16*(2), 862. https://doi.org/10.3390/en16020862

Putra, A. R. S., Czekaj, T. G., & Lund, M. (2019). Study of the biogas technology adoption as a livestock waste management among smallholder farmers in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *260*, 012070. https://doi.org/10.1088/1755-1315/260/1/012070

Rezaei, R., Safa, L., & Ganjkhanloo, M. M. (2020). Understanding farmers' ecological conservation behavior regarding the use of integrated pest management- an application of the technology acceptance model. *Global Ecology and Conservation*, *22*, Article e00941. https://doi.org/10.1016/j.gecco.2020.e00941
Richards, M. B., Wollenberg, E., & van Vuuren, D. (2018). National contributions to climate change mitigation from agriculture: Allocating a global target. *Climate Policy*, *18*(10), 1271–1285. https://doi.org/10.1080/14693062.2018.1430018
Rogers, E. M. (2003). *Diffusion of Innovations*. Simon and Schuster.
Röös, E., Bajželj, B., Smith, P., Patel, M., Little, D., & Garnett, T. (2017). Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures. *Global Environmental Change*, *47*, 1–12. https://doi.org/10.1016/j.gloenvcha.2017.09.001
Saris, W. E., Satorra, A., & Sörbom, D. (1987). The detection and correction of specification errors in structural equation models. *Sociological Methodology*, *17*, 105–129. https://doi.org/10.2307/271030
Savalei, V., & Bentler, P. M. (2006). Structural equation modeling. In R. Grover & M. Vriens (Eds.), *The handbook of marketing research* (pp. 330–334). Sage Publication. https://doi.org/10.4135/9781412973380.n17
Schoemaker, P. J. H. (1982). The expected utility model: Its variants, purposes, evidence and limitations. *Journal of Economic Literature*, *20*(2), 529–563. http://www.jstor.org/stable/2724488
Shao, Y., Wang, Z., Zhou, Z., Chen, H., Cui, Y., & Zhou, Z. (2022). Determinants affecting public intention to use micro-vertical farming: A survey investigation. *Sustainability*, *14*(15), 9114. https://doi.org/10.3390/su14159114
Sharifzadeh, M. S., Damalas, C. A., Abdollahzadeh, G., & Ahmadi-Gorgi, H. (2017). Predicting adoption of biological control among Iranian rice farmers: An application of the extended technology acceptance model (TAM2). *Crop Protection*, *96*, 88–96. https://doi.org/10.1016/j.cropro.2017.01.014
Sileshi, M., Kadigi, R., Mutabazi, K., & Sieber, S. (2019). Determinants for adoption of physical soil and water conservation measures by smallholder farmers in Ethiopia. *International Soil and Water Conservation Research*, *7*(4), 354–361. https://doi.org/10.1016/j.iswcr.2019.08.002
Sims, B., & Kienzle, J. (2017). Sustainable agricultural mechanization for smallholders: What is it and how can we implement it? *Agriculture*, *7*(6), 50. https://doi.org/10.3390/agriculture7060050
Singh, D., & Singh, P. (1977). New systematic sampling. *Journal of Statistical Planning and Inference*, *1*(2), 163–177. https://doi.org/10.1016/0378-3758(77)90021-0
Smith, P., & Gregory, P. J. (2013). Climate change and sustainable food production. *Proceedings of the Nutrition Society*, *72*(1), 21–28. https://doi.org/10.1017/S0029665112002832
Sotnyk, I., Kurbatova, T., Kubatko, O., Prokopenko, O., Prause, G., Kovalenko, Y., Trypolska, G., & Pysmenna, U. (2021). Energy security assessment of emerging economies under global and local challenges. *Energies*, *14*(18), 5860. https://doi.org/10.3390/en14185860
Stapleton, C. D. (1997). *Basic concepts and procedures of confirmatory factor analysis*. https://files.eric.ed.gov/fulltext/ED407416.pdf
Stevens, J. (1996). Categorical data analysis: The log linear model. In *Applied multivariate statistics for the social sciences* (3rd ed., pp. 518–557). Lawrence Erlbaum Associates.
Stock, R., Nyantakyi-Frimpong, H., Antwi-Agyei, P., & Yeleliere, E. (2023). Volta photovoltaics: Ruptures in resource access as gendered injustices for solar energy in Ghana. *Energy Research & Social Science*, *103*, 103222. https://doi.org/10.1016/j.erss.2023.103222
Taghizadeh-Hesary, F., & Yoshino, N. (2020). Sustainable solutions for green financing and investment in renewable energy projects. *Energies*, *13*(4), 788. https://doi.org/10.3390/en13040788
Tama, R. A. Z., Ying, L., Mark, Y., Hoque, M. M., Adnan, K. M. M., & Sarker, S. A. (2021). Assessing farmers' intention towards conservation agriculture by using the Extended Theory of Planned Behavior. *Journal of Environmental Management*, *280*, 111654. https://doi.org/10.1016/j.jenvman.2020.111654
Tan, C.-S., Ooi, H.-Y., & Goh, Y.-N. (2017). A moral extension of the theory of planned behavior to predict consumers' purchase intention for energy-efficient household appliances in Malaysia. *Energy Policy*, *107*, 459–471. https://doi.org/10.1016/j.enpol.2017.05.027
Taylor, S., & Todd, P. (1995a). Decomposition and crossover effects in the theory of planned behavior: A study of consumer adoption intentions. *International Journal of Research in Marketing*, *12*(2), 137–155. https://doi.org/10.1016/0167-8116(94)00019-K
Taylor, S., & Todd, P. (1995b). Understanding information technology usage: A test of competing models. *Information Systems Research*, *6*(2), 144–176. https://doi.org/10.1287/isre.6.2.144
Tran-Nam, Q., & Tiet, T. (2022). The role of peer influence and norms in organic farming adoption: Accounting for farmers' heterogeneity. *Journal of Environmental Management*, *320*, 115909. https://doi.org/10.1016/j.jenvman.2022.115909
Ulhaq, I., Pham, N. T. A., Le, V., Pham, H.-C., & Le, T. C. (2022). Factors influencing intention to adopt ICT among intensive shrimp farmers. *Aquaculture*, *547*, 737407. https://doi.org/10.1016/j.aquaculture.2021.737407
Ullman, J. B., & Bentler, P. M. (2012). Structural equation modeling. In I. Weiner, J. A. Schinka, & W. F. Velicer (Eds.), *Handbook of Psychology, Second Edition* (pp. 661–690). John Wiley & Sons. https://doi.org/10.1002/9781118133880.hop202023
Vanderpuye, I. N., Darkwah, S. A., & Živělová, I. (2020). The system of land ownership and its effect on agricultural production: The case of Ghana. *Journal of Agricultural Science*, *12*(5), 57–69. https://doi.org/10.5539/jas.v12n5p57
Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly*, *27*(3), 425–478. https://doi.org/10.2307/30036540
von Neumann, J., & Morgenstern, O. (1953). *Theory of games and economic behavior*. Princeton University Press .
Wang, Y.-n., Jin, L., & Mao, H. (2019). Farmer cooperatives' intention to adopt agricultural information technology—Mediating effects of attitude. *Information Systems Frontiers*, *21*, 565–580. https://doi.org/10.1007/s10796-019-09909-x
Wesseh, P. K., Jr., & Lin, B. (2017). Is renewable energy a model for powering Eastern African countries transition to industrialization and urbanization? *Renewable and Sustainable Energy Reviews*, *75*, 909–917. https://doi.org/10.1016/j.rser.2016.11.071
Yazdanpanah, M., Hayati, D., Hochrainer-Stigler, S., & Zamani, G. H. (2014). Understanding farmers' intention and behavior regarding water conservation in the Middle-East and North Africa: A case study in Iran. *Journal of Environmental Management*, *135*, 63–72. https://doi.org/10.1016/j.jenvman.2014.01.016
Yazdanpanah, M., Komendantova, N., & Zobeidi, T. (2022). Explaining intention to apply renewable energy in agriculture: The case of broiler farms in Southwest Iran. *International Journal of Green Energy*, *19*(8), 836–846. https://doi.org/10.1080/15435075.2021.1966792

Zeweld, W., Hidgot, A., & Hailu, G. (2017a). Impact of use of chemical fertiliser on farm households' risk behaviour and food security in Ethiopia. *Journal of Agricultural Extension*, *21*(2), 105–119. https://doi.org/10.4314/jae.v21i2.9

Zeweld, W., Van Huylenbroeck, G., Tesfay, G., & Speelman, S. (2017b). Smallholder farmers' behavioural intentions towards sustainable agricultural practices. *Journal of Environmental Management*, *187*, 71–81. https://doi.org/10.1016/j.jenvman.2016.11.014

Zhou, D., & Abdullah. (2017). The acceptance of solar water pump technology among rural farmers of northern Pakistan: A structural equation model. *Cogent Food & Agriculture*, *3*(1), Article 1280882. https://doi.org/10.1080/23311932.2017.1280882

Agricultural & Rural Studies

Article

Exploring the Effects of Climate Change on Rice Yields in Andhra Pradesh, India

Kotamraju Nirmal Ravi Kumar [1], Tatineni Ramesh Babu [2] , Kavanadala Rangaraju Hamsa [3], Adinan Bahahudeen Shafiwu [4,*] and Ishaque Mahama [5]

1 Department of Agricultural Economics, Acharya NG Ranga Agricultural University, Bapatla 522034, India; kn.ravikumar@angrau.ac.in
2 Vignan's Foundation for Science, Technology and Research, Guntur 522213, India; dean_saft@vignan.ac.in
3 College of Agriculture and Research Station, Indira Gandhi Krishi Vishwavidyalaya, Kurud 493663, India; hmmshamsa@gmail.com
4 Faculty of Agriculture, Food, and Consumer Sciences, University for Development Studies, Tamale P.O. Box TL1350, Ghana
5 Faculty of Social Science and Arts Departments, Simon Diedong Dombo University of Business and Integrated Development Studies, Wa P.O. Box 36, Ghana; imahama@ubids.edu.gh
* Correspondence: shafiwu@uds.edu.gh

Abstract: This study investigates the influence of climate change variables—namely rainfall, maximum temperature, and minimum temperature—on mean rice yields and yield variability across different agro-climatic zones in Andhra Pradesh during the Kharif and Rabi seasons. Utilizing Just and Pope production function, the research focuses on rice, a crucial crop for both seasons in the region. Drawing from panel data spanning 1998 to 2022, the study offers significant insights. During the Kharif season, increased rainfall, along with favorable maximum and minimum temperatures, positively correlates with higher mean rice yields and reduced yield variability. In contrast, during the Rabi season, only increased rainfall showed a significant impact on enhancing yields and minimizing variability, while temperature variables did not exhibit a substantial effect. Additionally, the time trend variable showed a positive and significant association with mean yield and yield variability in both seasons. Thus, technological advancement has contributed to improved rice yields and reduced variability. These findings underscore the importance of informed decision-making in sustainable rice cultivation, enabling farmers to effectively manage the impacts of climate change on yield and variability. By utilizing this knowledge, farmers can adapt their crop management strategies to optimize productivity and bolster the resilience of rice production in the face of evolving climatic conditions.

Keywords: rice; Andhra Pradesh; panel data; Just and Pope production function; elasticities

Check for updates

Citation: Kumar, K. N. R., Babu, T. R., Hamsa , K. R., Shafiwu, A. B., & Mahama , I. (2025). Exploring the Effects of Climate Change on Rice Yields in Andhra Pradesh, India. *Agricultural & Rural Studies*, *3*(1), 21. https://doi.org/10.59978/ar03010004

Received: 25 August 2024
Revised: 18 October 2024
Accepted: 24 December 2024
Published: 3 March 2025

1. Introduction

India, much like numerous other nations, faces significant challenges due to climate change. Alterations in rainfall patterns have led to increased precipitation and severe rainfall events in certain regions, resulting in floods and landslides. Conversely, other areas experience reduced rainfall, leading to droughts and water scarcity. Climate change has emerged as a critical global concern, attracting the attention of environmentalists because of its long-term adverse effects on agricultural production, food and water security, and rural livelihoods (Baig et al., 2022). Its impacts extend to the socio-economic and environmental realms, potentially causing widespread famines, migration, natural resource depletion, and economic instability. Agriculture is particularly vulnerable, bearing up to 80 percent of direct consequences, which significantly affect water availability, agricultural output, food security, and rural livelihoods. This multifaceted crisis highlights the need for a comprehensive strategy to mitigate the effects of climate change on agriculture and the broader socio-economic landscape. The ramifications transcend regional boundaries, permeating every household, as agricultural production and water resources are intrinsically linked in facilitating a plethora of goods and services. Consequently, climate change emerges as a formidable impediment to achieving sustainable agricultural development and ensuring food security. Regrettably, India is one of the susceptible nations to climate change, as evidenced by projections from earlier studies (Chaturvedi et al., 2012; Krishnan et al., 2020) indicating escalated rainfall and extreme temperatures, impeding timely crop sowing, growth, yields, and food security. According to Chaturvedi et al. (2012), mean warming across India is anticipated to range between 1.7 to 2.0 ˚C by the 2030s and 3.3 to 4.8 ˚C by the 2080s, with precipitation projected to surge by 4 to 5 percent by the 2030s and 6 to 14 percent by 2080s compared to the 1961–1990 baseline. Moreover, a consistent positive trend in extreme precipitation days (e.g., exceeding 40 mm/day) is anticipated for the decades beyond the 2060s. While climate variability is a global predicament, its impact on agriculture is particularly acute for emerging economies, notably Asian and African nations (Chandio et al., 2022b). Given farmers limited financial resources to mitigate environmental impacts on agriculture, climate change presents a formidable challenge for economists, agronomists, and policymakers (Chandio et al., 2022d). This highlights the necessity for a rigorous examination of climate change's impact and variability on crop yields and the consequent development of climate-resilient crop varieties and technologies tailored to evolving climatic scenarios. Addressing these issues is crucial to safeguarding agricultural sustainability and ensuring the resilience of rural communities amidst the growing threat of climate change. Agriculture is particularly vulnerable, with climate change disrupting crop growth, water availability, and pest dynamics. The State of Andhra Pradesh boasts diverse agro-climatic zones, encompassing coastal regions, upland areas, hot and humid regions, and semi-arid regions. Rice, a staple food crop in Andhra Pradesh, is cultivated across these diverse zones. It constitutes approximately 40 percent of India's total foodgrain production and accounted for 16 percent of global rice production in 2021–22 (Directorate of Economics and Statistics, 2022).

Andhra Pradesh ranked eighth in India in rice production, contributing 7.79 million tonnes accounting for 5.98 percent of the country's rice production during 2021–22. Notably, the average rice yield in Andhra Pradesh (3470 kg/ha) surpasses the national average (2809 kg/ha) in 2021–22 (Figure 1; Directorate of Economics and Statistics, 2022). Rice cultivation in Andhra Pradesh spans both the Kharif and Rabi seasons across diverse agro-climatic zones, including the Scarce Rainfall Zone, Southern Zone, Krishna Zone, Godavari Zone, and North Coastal Zone. Rice plays an indispensable role in the agricultural economy of Andhra Pradesh, serving as both a staple food and a critical source of livelihood for millions of farmers. Its importance is accentuated by the state's diverse agro-climatic zones, each uniquely suited for rice cultivation. The crop's prevalence in both the Kharif and Rabi seasons underscores its significance, as it sustains food security and economic stability throughout the year. Rice cultivation is heavily dependent on climatic factors, particularly rainfall and temperature, making these variables crucial for understanding seasonal crop dynamics. In the Kharif season, which aligns with the monsoon, rainfall is the primary determinant of rice growth, affecting both water availability and soil conditions necessary for optimal yields. Conversely, the Rabi season relies on residual moisture and supplemental irrigation, making temperature a more critical factor, as it influences crop maturation and water requirements. Any fluctuations in these climate variables, such as altered precipitation patterns or increased temperature extremes, can have profound effects on rice productivity, leading to variability in yields. Thus, analyzing the impacts of climate change on these variables across both seasons is essential for ensuring the resilience of rice farming, safeguarding food security, and formulating effective adaptation strategies in the face of climate-induced risks. However, the rice cultivating agro-climatic zones experience heterogeneous impacts from climate change (Mendelsohn & Williams, 2004; Gbetibouo & Hassan, 2005), necessitating research that employs more disaggregated climate, area, and yield data to comprehensively understand its impact on rice yields. Rice is a staple crop, making it crucial to understand climate change effects on its yields to evaluate potential disruptions to food security and availability. Investigating these impacts helps identify specific challenges and vulnerabilities, guiding the development of adaptation strategies and policies to mitigate adverse effects and enhance resilience. Additionally, given the substantial water usage in rice cultivation, understanding climate change's impact on yields can inform effective water management strategies. Scientific research in this domain provides valuable evidence for policymakers and decision-makers, aiding the formulation of climate-resilient agricultural policies and sustainable farming practices. This research specifically aims to scrutinize variations in climate change variables and rice yields across selected districts during the Kharif and Rabi seasons. It seeks to understand how changes in climate variables affect both the average and variability of rice yields throughout these seasons. Furthermore, the study endeavors to estimate the elasticities of climate change configurations to forecast future rice yields for both seasons, thereby offering insights for proactive agricultural planning and policy formulation.

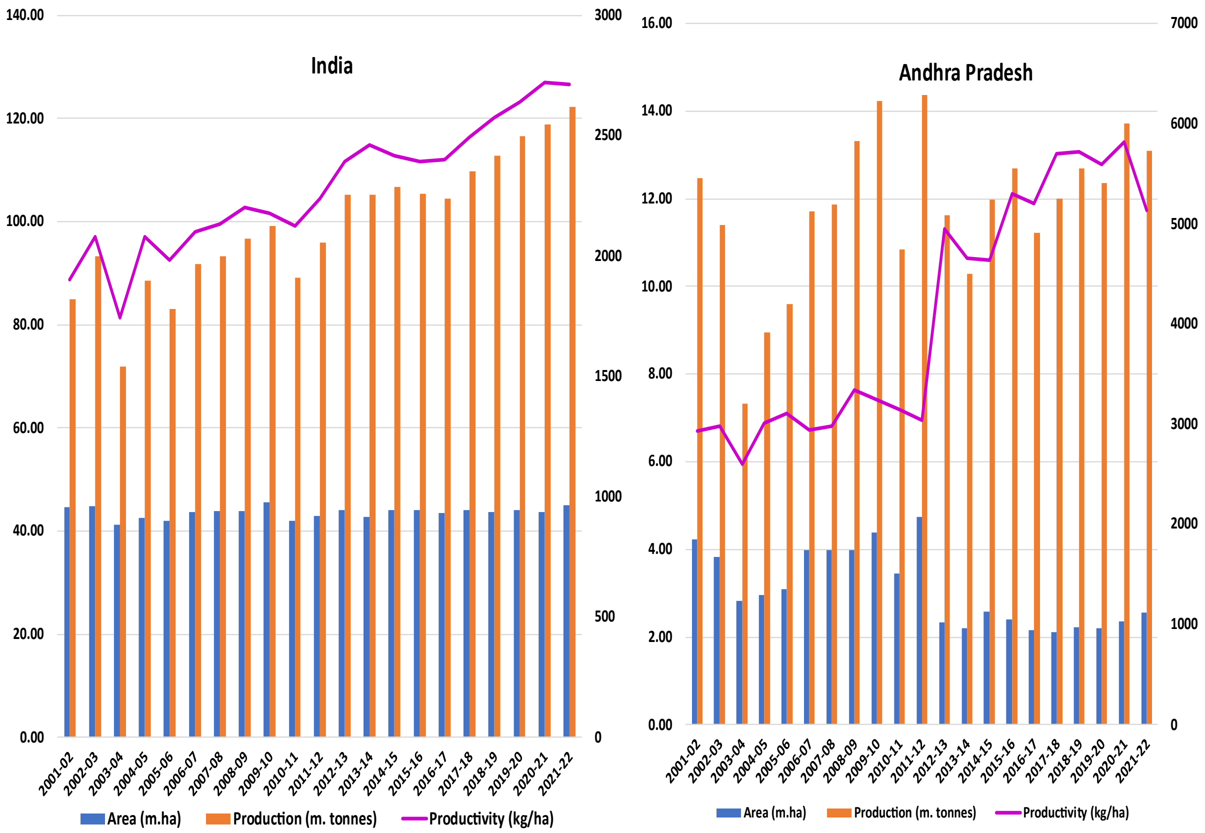


Figure 1: Trends in Area, Production and Productivity of Rice in India and Andhra Pradesh (2001–02 to 2021–22).

This study aims to address specific gaps in existing research on the impact of climate change on rice yields in Andhra Pradesh, with a focus on the Kharif and Rabi seasons. While several studies have examined the broader impacts of climate change on agriculture in India, few have conducted an in-depth, district-level analysis that considers the unique agro-climatic zones of Andhra Pradesh. Many existing studies, such as those by Gupta and Mishra (2019), Saud et al. (2022), and Singh et al. (2024), have explored the heterogeneous impacts of climate change on agriculture across different regions, but this research brings a more granular focus by disaggregating climate, area, and yield data across specific zones within Andhra Pradesh. A key gap this study addresses is the absence of detailed insights into how climate variables such as rainfall and temperature uniquely affect rice yields across both seasons in the state's diverse agro-climatic zones. For instance, while previous research may have assessed the overall vulnerability of crops to climate change, there is limited analysis of how Kharif and Rabi season-specific climate variations influence rice productivity, especially with regard to water availability and temperature fluctuations. This research also seeks to contribute uniquely by estimating the elasticities of climate variables, offering a forecast of future rice yields under different climate change scenarios. By doing so, it provides critical insights for policymakers and agricultural planners, particularly with respect to formulating targeted adaptation strategies for different agro-climatic regions. In comparison to broader studies that may not focus on the seasonal and spatial complexities of rice cultivation in Andhra Pradesh, this research adds value by delivering district-specific, data-driven recommendations, ensuring more precise and regionally tailored policy interventions. This nuanced approach fills an existing gap by not only exploring the variability of rice yields across seasons but also offering forward-looking solutions for mitigating the adverse effects of climate change on rice production in the region.

This study significantly advances existing research by incorporating several novel elements. Firstly, it enhances the current literature by utilizing homogeneity and inhomogeneity calculations to identify breakpoints in climate change data, specifically analyzing rainfall patterns and maximum and minimum temperatures over a period of two and a half decades. Secondly, by focusing on Andhra Pradesh, the research addresses a critical gap and provides valuable insights for formulating climate-resilient strategies in rice cultivation. Thirdly, the study employs an extensive panel dataset spanning nearly two and a half decades (1998–2022). This extended timeframe is particularly valuable for capturing the gradual impacts of climate change, which manifest over long periods. The dataset surpasses those used in previous studies, such as Mandal and Singha (2020) and

Carew et al. (2017), thereby offering a more comprehensive and reliable assessment of climate change's impact on rice yields. Fourthly, the research delves into the granular level of districts specializing in rice cultivation across diverse agro-climatic zones in Andhra Pradesh, providing a nuanced analysis. Lastly, the study focuses exclusively on the major rice-cultivating districts in Andhra Pradesh, ensuring that the findings are highly relevant and targeted. This comprehensive approach enables policymakers to formulate effective climate-resilient agricultural policies. By doing so, it overcomes the limitations of aggregation anomalies that may arise considering country-level panel data. Given the significant climate divergence across different states in India, generalizing findings at the all-India level would not yield meaningful results. This approach is in tune with the studies such as Gadedjisso-Tossou et al. (2021), Mandal and Singha (2020), and Carew et al. (2017).

2. Review of literature

Many researchers have analyzed the impact of climate change variables on crop yields at the global level and in India, in particular (Table 1).

Table 1. Summary of empirical investigations.

Authors	Country	Time period	Methodology employed	Major research findings
Gadedjisso-Tossou et al. (2021)	Northern Togo, West Africa	1977–2012	Multiple regression analysis	There exists a non-linear and significant relationship between rainfall and temperature on the yields of cereals. Squared terms of both rainfall and temperature have a positive influence on yield.
Mandal & Singha (2020)	Assam, India	Panel data (1991–2013)	Just & Pope (1978) approach	Rising temperatures can have harmful impacts on the average yields of summer rice and mustard. Daily average mean temperature has a non-linear impact on yield variability of summer rice, winter rice, and potato.
Shayanmehr et al. (2020)	Iran	1961–2010	Just and Pope Production Function – Quadratic and Cobb-Douglas forms	Minimum temperature showed a positive influence on mean yield of spring potato. Increase in rainfall exerted a negative influence on potato yield. Maximum temperature showed a negative association with potato yield.
Verma et al. (2020)	India	1966–2011	Just and Pope stochastic production function	Rice yields are reduced by rainfall extremes. Extremely high temperatures negatively influenced the yields of millets.
Mulungu et al. (2021)	Zambia	1981–2011	Just and Pope stochastic production function	Negative impact of temperature rise on maize and beans yields. Positive impact of rainfall rise on yields.
Saei et al. (2019)	Iran	Panel data (1983 to 2014)	Just and Pope Production Function – Quadratic and Cobb-Douglas forms	Rainfall showed a positive influence on yields of maize and wheat. Minimum temperature is yield risk decreasing factor. Both time trends and regional dummies were statistically significant in boosting maize and wheat yields.
Carew et al. (2017)	Manitoba, Canada	1996–2012	Just and Pope Production Function – Cobb-Douglas form	Variety richness reduces yield variability in wheat, unlike varieties protected by plant breeders' rights. Application of Phosphorus fertilizers showed a positive influence on mean yield Total precipitation, June and July temperatures had a negative influence on mean yield.

The studies reviewed above employ a variety of methodologies to investigate how climate variables affect crop yields. These methodologies offer a nuanced examination of the intricate relationships between climate factors—such as rainfall and temperature—and agricultural productivity. With this background, researchers present the complex dynamics of climatic change impact on rice yields in Andhra Pradesh. Panel data analysis proves invaluable in several studies by considering temporal trends and regional variations. This approach facilitates a deeper understanding of how climate impacts evolve over time and vary across different geographic areas.

3. Methodology

3.1. Study Area and Data Collection

Five distinct agro-climatic zones in Andhra Pradesh were deliberately selected for this study. These zones include the Scarce Rainfall zone, Southern zone, Krishna zone, Godavari zone, and North Coastal zone (Figure 2). Specific districts were purposefully chosen from each zone during the Kharif season (Table 2). These districts—Kurnool, Kadapa, Krishna, West Godavari, and Srikakulam—collectively account for 51.97 percent of the total rice-cultivated area (1.53 m. hectares) in Andhra Pradesh. Similarly, for the Rabi season, the study selected Kurnool, Chittoor, Krishna, West Godavari, and Srikakulam districts, one from each of the aforementioned agro-climatic zones. These districts collectively represented 40.24 percent of the total rice cultivated area (0.83 m. hectares). The study relied on a diverse set of data sources to capture historical climate and agricultural variables, facilitating a detailed analysis of the relationship between climate change and rice yield variability in Andhra Pradesh. Climate observations from 1998 to 2022 were collected, focusing on monthly rainfall, maximum and minimum temperatures, which are key variables in determining crop yield. These data were gathered from the Statistical Abstract of Andhra Pradesh and the Handbook of Statistics of the selected districts, available through the Directorate of Economics and Statistics, Andhra Pradesh Additionally, supplementary climate data were sourced from the NASA POWER web portal (https://power.larc.nasa.gov/data-access-viewer/), which provides global data on surface meteorological and solar energy parameters. The panel structure of the study covered five distinct agro-climatic zones—Scarce Rainfall, Southern, Krishna, Godavari, and North Coastal—spanning over five selected districts: Kurnool, Kadapa, Krishna, West Godavari, and Srikakulam during the Kharif season, and Kurnool, Chittoor, Krishna, West Godavari, and Srikakulam during the Rabi season. The panel consists of 25 years of data (1998–2022) across these five districts in two seasons, offering a comprehensive dataset to examine both temporal and spatial variations in climate factors and their impact on rice yield variability.

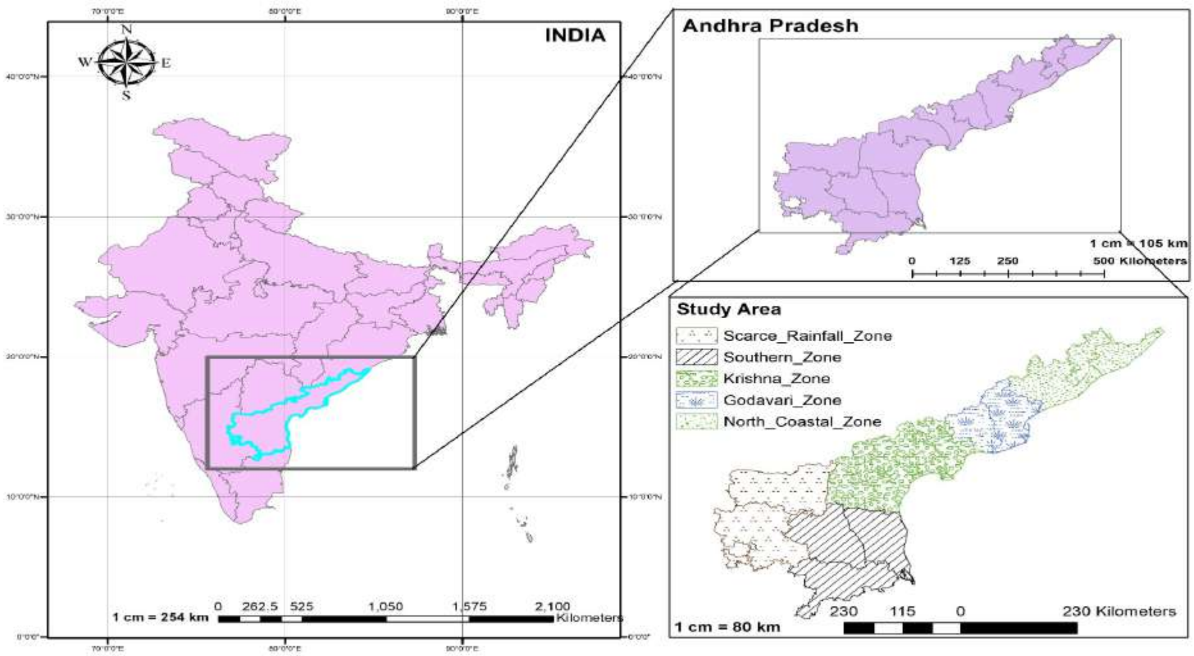


Figure 2. Selected agro-climatic zones in Andhra Pradesh.

Table 2. Seasons of cultivation of rice across different agro-climatic zones in Andhra Pradesh.

Seasons	Sowing period	Harvesting period	Period of growth#	Source
Kharif rice	June to August	October to November	June to October	Regional Agricultural Research Stations (RARSs) of ANGRAU
Rabi rice	October to November	February to March	October to February	

Note: # - Considering the period from middle of sowing to middle of harvesting period.

The data sources provided historical monthly rainfall and temperature data, crucial for analyzing climate impacts on rice yields. NASA POWER, for instance, offers high-resolution global data on surface meteorological parameters, which were used to complement the state and district-level data when local records were incomplete or inconsistent. However, obtaining accurate and granular rainfall and temperature data at the district level posed some challenges. First, while the Directorate of Economics and Statistics of Andhra Pradesh provides detailed historical climate data and rice yields, there were occasional gaps or inconsistencies in district-level records, particularly in earlier years. This was especially problematic for some agro-climatic zones where local data collection methods were less robust. To address these gaps, climate data from NASA POWER was used as supplementary information, as it provides consistent, high-resolution climate data derived from satellite observations and models. This ensured continuity in the climate records and allowed for the creation of a more complete dataset. Furthermore, any discrepancies between different data sources were resolved through cross-referencing and validation against available local weather station records, where possible. Data processing involved cleaning, standardizing, and organizing the climate variables (monthly rainfall, maximum and minimum temperatures) to create a panel dataset compatible with the districts and time periods under study. Advanced statistical techniques, such as interpolation, were employed to fill minor gaps in the dataset, ensuring consistency across years and districts. The processed data were then integrated with the agricultural yield data, creating a robust dataset for further econometric analysis, facilitating the exploration of how climate variability has affected rice production across different agro-climatic zones and time periods.

3.2. Descriptive Statistics

Mean, Standard Deviation (SD), and Coefficient of Variation (CV) are employed to examine the variability among climate change variables viz., rainfall, maximum and minimum temperatures and yields of rice during both Kharif season (June to September) and Rabi season (October to January).

3.3. Panel Unit Roots and Stationarity

Unit root for each variable was tested (with trend and without trend) through employing Fisher-type test (Maddala & Wu, 1999); Levin, Lin, Chu (LLC) test (Barnwal & Kotani, 2010) and Harris-Tzavalis test (Harris & Tzavalis 1999; to ensure the robustness of the results), as non-stationary data set might yield spurious results (Chen & Chang, 2005; Granger & Newbold, 1974).

3.4. Just and Pope Production Function

Earlier studies (Rao et al., 2016; Rao et al., 2017) have furnished climate change in Andhra Pradesh. The projections until 2050 in Andhra Pradesh encompass temperature increases of up to 1.5 degrees Celsius in summer and 2 degrees Celsius in winter, with Kharif rainfall anticipated to rise by 13 to 34 percent and Rabi rainfall by 6 to 45 percent. This climate shift is characterized by escalating temperatures, particularly nocturnal temperatures, alterations in rainfall patterns, and a heightened frequency of extreme weather events (droughts, floods, heatwaves, and cold spells). Just and Pope's (1978; 1979) production function was employed to analyze the impact of climate change variables on the mean yield and yield variability of rice during both Kharif and Rabi seasons. Two functional forms of the Just and Pope production function viz., Quadratic and Cobb-Douglas forms are considered.

3.4.1 Mean Function

This is specified as:

Linear-Quadratic form: $$y = \alpha_0 + \alpha_t T + \sum_j \alpha_{1j} x_j + \sum_j \alpha_{2j} x_j^2 + \sum_j \sum_{(k \neq j)} \alpha_{jk} x_j x_k$$

Cobb-Douglas form: $$y = \alpha + \alpha T + \prod_j x_j^{\alpha_j}$$

where x_j *and* x_k represent explanatory variables, "T" represents time trend and $\alpha's$ are coefficients to be estimated.

3.4.2. Variance Function

The variability function h(.) is modelled as a Cobb-Douglas form (Just & Pope, 1978; 1979; Kumbhakar & Tveteras, 2003; Koundouri & Nauges, 2005):

$$h(x) = \beta T \prod x\beta_j \quad \text{or} \quad h(x) = \beta T x\beta_1 \cdot x\beta_2 \cdot x\beta_3 \cdot\cdots\cdot x\beta_n$$
$$\ln h(x) = \ln(\beta T \beta t x\beta_1 \cdot x\beta_2 \cdot x\beta_3 \cdot\cdots\cdot x\beta_n)$$
$$\ln h(x) = \ln\beta + \ln T\beta t + \ln x\beta_1 + \ln x\beta_2 + \ln x\beta_3 + \cdots + \ln x\beta_n$$
$$\ln h(x) = \ln\beta_0 + \beta t \ln T + \beta_1 \ln x_1 + \beta_2 \ln x_2 + \beta_3 \ln x_3 + \cdots + \beta_n \ln x_n$$

Specification tests are conducted to ensure the reliability, accuracy, and interpretability of estimated relationships and predictions (Judge et al., 1985; Cameron & Trivedi, 2009). Additionally, elasticities of climate change variables and future predictions of rice yields during both the Kharif and Rabi seasons are analyzed (Kabir, 2015; Sanjay et al., 2017).

Employing two functional forms, namely the Quadratic and Cobb-Douglas forms, enhances robustness, accommodating different responses of yield to climate change. Moreover, previous research supports the efficacy of this function in diverse agricultural contexts (Cabas et al., 2010; Kim & Pang, 2009; Tveterås, 1999; Tveterås & Wan, 2000; Chen et al., 2004; Isik & Devadoss, 2006; Koundouri & Nauges, 2005).

The Just and Pope production function is well-suited for analyzing risk and uncertainty in agricultural production, particularly in the context of climate change. This model separates the mean yield from the yield variability, allowing for a clearer distinction between the average effects of climate variables and the risks associated with their variability. By incorporating both the mean function (which captures the systematic impact of inputs and climate factors on yield) and the variance function (which models the variability of yields), the model directly addresses uncertainty in agricultural outcomes. The variance function, specified in a Cobb-Douglas form, links variability to climate and other input variables, capturing how changes in factors such as temperature, rainfall, and extreme weather events affect not just the mean yield but also its stability. This allows for an estimation of how sensitive yields are to different climate risks, providing insights into the risk management strategies needed for both the Kharif and Rabi seasons.

As for the application of the model, it is typically applied separately for the two seasons to capture the unique climatic and agronomic conditions present during Kharif and Rabi. Each season has distinct rainfall patterns, temperature fluctuations, and crop management practices, making it necessary to estimate the mean and variance functions independently for each. This season-wise approach ensures a more accurate representation of the climate-yield relationship and accounts for seasonal variations in risk and uncertainty.

This study hypothesizes that climate change impacts rice yields in Andhra Pradesh in several ways. First, variations in seasonal rainfall, particularly during the Kharif and Rabi seasons, significantly affect rice yields, with excessive rainfall during Kharif leading to waterlogging and reduced yields, while inadequate rainfall during Rabi creates water stress that diminishes output. Second, extreme temperatures, especially during critical growth stages, are expected to have a significant negative impact on rice yields, with higher temperatures during the Rabi season being particularly detrimental due to the crop's reliance on irrigation and temperature-sensitive growth phases. Third, the impact of climate change on rice yields is likely to vary across districts, with coastal regions more vulnerable to increased rainfall and flooding, while inland areas are more prone to temperature fluctuations and droughts, resulting in varying degrees of climate sensitivity across different agro-climatic zones. Finally, long-term projections of climate variables, such as rainfall and temperatures, are expected to increase rice yields in both seasons, and the study aims to estimate the elasticity of these climate variables to forecast future rice productivity and inform targeted adaptation strategies.

4. Results and Discussion

4.1. Summary Statistics

Table 3 shows that Srikakulam exhibited the highest mean rainfall of approximately 767 mm during the Kharif season spanning from 1998 to 2022. Following closely is West Godavari with 747 mm and Krishna with 693 mm. In stark contrast, Kadapa and Kurnool, situated in the arid Rayalaseema region, recorded the lowest mean rainfall of 436 mm and 439 mm, respectively. The substantial coefficient of variation (CV) values (> 90%) underscores the erratic nature of rainfall distribution across all surveyed districts. Conversely, minimal variation is observed for both maximum temperature and minimum temperature among the selected districts. When examining agricultural yields, Kurnool exhibited the highest variability at 45.56 percent, trailed by Kadapa at 22.02 percent. In contrast, the coastal districts of Srikakulam, West Godavari, and Krishna, benefitting from perennial rivers (Nagavali, Godavari, and Krishna respectively), displayed lower yield variability due to consistent water supply.

Table 3. Summary statistics of selected variables (1998–2022).

District	Variables	Mean	CV(%)	Minimum	Maximum
Kharif season					
Kurnool	Yield (t/ha)	4.01	45.56	0.23	1.15
Kurnool	Rainfall (mm)	438.90	129.89	263.90	872.70
Kurnool	Max. Temp (˚C)	33.92	2.83	32.24	35.66
Kurnool	Min. Temp (˚C)	24.65	2.12	23.84	25.81
Kadapa	Yield (t/ha)	4.09	22.02	0.17	9.69
Kadapa	Rainfall (mm)	435.50	90.70	270.40	572.50
Kadapa	Max. Temp (˚C)	36.25	1.42	32.67	38.21
Kadapa	Min. Temp (˚C)	25.88	1.66	21.06	27.14
Srikakulam	Yield (t/ha)	2.63	0.94	0.81	4.46
Srikakulam	Rainfall (mm)	766.60	125.40	571.00	1055.00
Srikakulam	Max. Temp (˚C)	32.69	0.88	31.39	34.62
Srikakulam	Min. Temp (˚C)	26.55	0.47	25.85	27.87
Krishna	Yield (t/ha)	4.23	1.28	2.07	6.24
Krishna	Rainfall (mm)	693.00	160.70	418.90	1090.10
Krishna	Max. Temp (˚C)	34.07	0.83	32.86	36.20
Krishna	Min. Temp (˚C)	24.13	1.53	21.75	26.17
West Godavari	Yield (t/ha)	3.39	1.34	1.88	6.24
West Godavari	Rainfall (mm)	746.70	171.40	418.90	1090.10
West Godavari	Max. Temp (˚C)	33.43	1.01	31.54	36.20
West Godavari	Min. Temp (˚C)	25.26	1.79	21.75	27.55
Rabi season					
Kurnool	Yield (t/ha)	3.89	28.26	2.8	5.9
Kurnool	Rainfall (mm)	131.10	48.43	14.60	257.00
Kurnool	Max. Temp (˚C)	31.82	3.26	30.07	33.70
Kurnool	Min. Temp (˚C)	20.66	4.27	19.54	22.34
Chittoor	Yield (t/ha)	3.79	32.74	2.44	5.80
Chittoor	Rainfall (mm)	349.60	46.06	158.10	753.00
Chittoor	Max. Temp (˚C)	31.40	2.75	30.45	33.50
Chittoor	Min. Temp (˚C)	22.00	3.40	20.52	23.66
Srikakulam	Yield (t/ha)	3.07	30.47	2.11	4.80
Srikakulam	Rainfall (mm)	235.00	67.50	29.80	620.00
Srikakulam	Max. Temp (˚C)	30.75	2.92	29.21	31.90
Srikakulam	Min. Temp (˚C)	23.15	3.99	21.80	25.00
Krishna	Yield (t/ha)	4.31	25.90	3.01	6.68
Krishna	Rainfall (mm)	247.20	52.98	60.60	498.00
Krishna	Max. Temp (˚C)	30.82	4.17	29.10	33.70
Krishna	Min. Temp (˚C)	18.78	6.17	16.70	20.23
West Godavari	Yield (t/ha)	4.73	10.58	3.93	5.83
West Godavari	Rainfall (mm)	212.90	58.53	44.30	493.10
West Godavari	Max. Temp (˚C)	30.47	3.41	29.03	32.00
West Godavari	Min. Temp (˚C)	22.03	6.13	17.30	23.10

Note: Figures in parentheses indicate "Z-cal" value, ** - Significant at 1% level, * - Significant at 5% level.

An interesting observation is that Chittoor, a district in the Rayalaseema region, received the highest mean rainfall (349.60 mm) during the Rabi season. Furthermore, Chittoor exhibited the lowest variability in rainfall, as it receives most of its rain from the northeast and retreating monsoons during the winter season. Frequent low-pressure systems in the Bay of Bengal during this period also lead to heavy rainfall. However, despite the higher mean rainfall, Chittoor also exhibited higher yield variability in Rabi season. The same was higher in all three coastal districts (Srikakulam, West Godavari, and Krishna) compared to Kharif season. Furthermore, both maximum and minimum temperatures exhibited higher magnitudes and variability during Rabi season compared to Kharif season.

Regarding rice productivity during the Kharif season, Krishna demonstrated the highest yield at 4.23 t/ha, followed by Kadapa at 4.09 t/ha and Kurnool at 4.01 t/ha. In contrast, Srikakulam had the lowest productivity with only 2.63 t/ha. However, in the Rabi season, rice productivity increased across all three coastal districts: Srikakulam (3.07 t/ha), Krishna (3.94 t/ha), and West Godavari (4.73 t/ha), as these districts enjoy assured irrigated conditions facilitated by the three perennial rivers in the coastal regions. While the coastal districts outperformed the others in terms of yield during Rabi season, they also exhibited considerable yield variability.

4.2. Pre-Estimation Specification Tests

ADF-Fisher-type, LLC test, and Harris-Tzavalis test (Poudel & Kotani, 2013; Sarker et al., 2019) are employed to assess stationarity, considering both constant and trend specifications for the respective series. The results (Table 4) showed that selected variables were stationary for all equations (McCarl et al., 2008; Kim & Pang, 2009). The findings from the modified Wald test, Breusch-Pagan/Cook-Weisberg test, Breusch-Pagan-Godfrey (BPG), and White heteroscedasticity tests (Table 5) indicated the presence of heteroscedasticity and this does not impede the application of Just-Pope model. Furthermore, Breusch-Pagan LM test of independence and Wooldridge test indicated the absence of aggregation bias and contemporaneous correlation. The Variance Inflation Factor test revealed the absence of multicollinearity among independent variables. Hausman test revealed fixed effect model was more appropriate than the random effect model.

Table 4. Panel unit root test results (1998–2022).

Variables	Fisher-ADF (Modified inv. Chi-squared)		LLC (Adjusted t*)		Harris-Tzavalis (rho)	
	Trend	Without trend	Trend	Without trend	Trend	Without trend
Kharif season						
Yield (t/ha)	4.6587**	5.0554**	−3.3811**	−3.9972**	0.0201 (−6.7679)**	0.3237 (−8.0643)**
Rainfall (mm)	16.9481**	17.5451**	−2.3230*	−2.5407**	−0.2460 (−9.5864)**	−0.1083 (−14.5939)**
Maximum Temp (˚C)	7.1499**	8.5659**	−4.0732**	−4.1641**	0.0859 (−6.0710)**	0.2686 (−8.8960)**
Minimum Temp (˚C)	4.7012**	4.7153**	−12.9912**	−8.6574**	0.3832 (−2.9222)**	0.4607 (−5.9935)**
Rabi season						
Yield (t/ha)	3.8943**	4.1083**	−3.2118**	−3.8936**	0.0311 (−6.9113)**	0.3518 (−9.3815)**
Rainfall (mm)	14.9581**	17.3439**	−3.4779**	−3.6349**	−0.1785 (−8.8708)**	−0.1332 (−14.9711)**
Maximum Temp (˚C)	5.2897**	6.3307**	−3.4404**	−2.6426**	0.1657 (−5.2257)**	0.5741 (−4.2784)**
Minimum Temp (˚C)	3.7880**	3.3359**	−3.1552**	−2.7703**	0.1463 (−5.4315)**	0.4182 (−6.6353)**

Note: Figures in parentheses indicate "Z-cal" value, ** - Significant at 1% level, * - Significant at 5% level.

Table 5. Panel data model specification tests (1998–2022).

Heteroscedasticity				Aggregation bias (Contemporaneous Correlation (CC))	VIF	Autocorrelation	Fixed effect vs Random effect
Modified Wald test for group-wise heteroskedasticity	**Breusch-Pagan / Cook-Weisberg test**	**Breusch-Pagan-Godfrey (BPG) Test**	**White test**	**Breusch-Pagan LM test of independence**		**Wooldridge test**	**Hausman test**
Kharif season							
χ^2 (5) = 1613.56**	$\chi^2(1)$ = 5.25**	F(3, 121) = 4.01**	F(2, 122) = 5.07**	$\chi^2(10)$ = 6.2793^{NS}	< 2.31 for all independent variables	F(1, 4) = 0.039^{NS}	$\chi^2(3)$ = 8.26** (Fixed effect is appropriate)
Rabi season							
χ^2 (5) = 1262.69**	$\chi^2(1)$ = 3.94**	F(3, 121) = 5.33**	F(2, 122) = 4.27**	$\chi^2(10)$ = 4.1109^{NS}	< 1.149 for all independent variables	F(1, 4) = 0.157^{NS}	$\chi^2(3)$ = 4.16** (Fixed effect is appropriate)

Note: ** - Significant at 1% level, NS - Non-Significant

4.3. Just and Pope Production Function

4.3.1. Determinants of Mean Yield and Variability During Kharif Season

The findings from Table 6 suggest that climate variables showed a significant influence on the mean yield of rice, as observed in both quadratic and Cobb-Douglas models. Specifically, rainfall, maximum and minimum temperatures exerted positive and significant influences on mean yield of rice. An increase in rainfall, unless it reaches high-intensity levels leading to floods and subsequent crop inundation, can enhance the production and productivity of Kharif rice. Similarly, higher maximum and minimum temperatures indicate a cloud-free climate, increased sunshine hours, and higher night temperatures, which promote photosynthetic activity and assimilation, ultimately leading to improved rice yields.

Table 6. Estimates of Just and Pope function during Kharif season.

S.No	Variables	Quadratic model				Cobb-Douglas model			
		Mean Yield		Yield Variability		Mean Yield		Yield Variability	
		Coeffi-cient	SE	Coeffi-cient	SE	Coeffi-cient	SE	Coeffi-cient	SE
1	Rainfall	0.0049**	0.0011	−0.0044*	0.0021	0.9143**	0.2096	−0.8199**	0.1503
2	Max.Temp	0.3922**	0.0903	−0.0059*	0.0029	0.0353**	0.0098	−0.0519**	0.0082
3	Min.Temp	0.2257**	0.0416	−0.0007*	0.0003	0.0251*	0.0117	−0.0011**	0.0003
4	Time trend	0.0583**	0.0139	0.0636**	0.0157	0.1305**	0.0492	0.0105**	0.0029
5	$Rain^2$	−0.0006**	0.0002	0.0014*	0.0006	-	-	-	-
6	$Max.Temp^2$	−0.0848**	0.0368	0.1054**	0.0199	-	-	-	-
7	$Min.Temp^2$	0.0226	0.0453	−0.2789	0.1730	-	-	-	-
8	Rain*Max.Temp	0.0011**	0.0003	−0.0027**	0.0009	1.0474**	0.2248	21.0972	32.4152
9	Rain* Min.Temp	−0.0003	0.0002	−0.0015	0.0012	−5.8737	3.7877	−32.7552	18.9765
10	Max.Temp * Min.Temp	−0.2601	0.1625	0.1133	0.1876	−99.1974	54.6398	−113.9324	377.2511
11	D2-Kadapa	1.9734**	0.4979			0.7233**	0.2454		
12	D3-Srikakulam	1.4797**	0.5103			1.1108**	0.2977		
13	D4-Krishna	3.1585**	0.2861			1.5304**	0.3271		
14	D5-West Godavari	2.3445**	0.4705			1.3375**	0.2952		
	Constant	335.3549	60.4899	312.0852	172.098	1194.2115	489.4903	1.0825	3.3584
	Model statistics								
	Observations (n)	125		125		125		125	
	F test (14, 110)	53.41**		F(14, 110) = 2.75**		F test (11, 113) = 42.26**		F(11, 113) = 3.42**	
	Prob > F	0.0000		0.0022		0.0000		0.0004	
	R^2 Adj	0.8811				0.7631			

Note: ** - Significant at 1% level, * - Significant at 5% level.

The significant time trend variable ($p < 0.00$) in the mean functions indicates that technological progress, including improved varieties, better seed, agronomic practices, and plant protection measures, has positively influenced rice yield over the reference period (Isik & Devadoss, 2006; Sarker et al., 2014; Sinnarong et al., 2019). However, the lower magnitude of the time trend variable is due to the excessive use of resources such as seeds, fertilizers, pesticides, and weedicides beyond the scientific recommendations. Additionally, all four district dummies showed a positive influence on mean yield. This suggests that the yield of rice in these districts significantly differs from the benchmark mean yield of Kurnool.

In the quadratic model, the quadratic terms for rainfall and maximum temperature exhibited negative coefficients, indicating a threshold, beyond which these variables adversely affect the mean yield of rice. Specifically, excessive rainfall leading to prolonged submergence of crops for more than a week during its growth stage will adversely affect productivity. This suggests proper water management and drainage practices to mitigate potential crop damage from excessive rainfall. Conversely, the influence of maximum temperature on mean yield is positive when temperatures remain below 40 °C during the Kharif season. However, prolonged exposure to high maximum temperatures, particularly during dry spells, can result in decreased leaf area, increased senescence rate, shortened growing periods, and ultimately reduced rice yields (Kumar et al., 2015; Srivastava et al., 2019; Vashisht et al., 2015; Resop et al., 2014). In contrast, minimum temperature during sowing and growth stages demonstrates a positive influence on mean yield. In yield variability/risk functions of both quadratic and Cobb-Douglas models, negative and significant effects of rainfall, maximum and minimum temperatures are observed. These factors contribute to decreased variability in rice yield, resulting in a more consistent and stable production. The positive association of the time trend variable with yield variability underscores the role of technological advancements and other temporal factors in enhancing production stability.

In quadratic model, squared terms of rainfall and maximum temperature show positive and significant influences on yield variability, indicating that beyond certain thresholds, higher levels of these variables lead to increased yield variability. This suggests a higher degree of uncertainty and instability in rice production under such conditions. These findings emphasize the presence of threshold effects and the necessity for considering non-linear relationships in understanding the dynamics of rice yield variability (Chen et al., 2004; Kumar et al., 2015).

4.3.2. Determinants of Mean Yield and its Variability of Rice During Rabi Season

As per the findings presented in Table 7, both the quadratic and Cobb-Douglas models indicate that only rainfall exhibits a positive and significant influence on the mean yield of rice. This underscores the critical role of adequate moisture in the soil, alternating wet and dry periods, and favorable conditions during crucial growth stages such as tillering and panicle initiation in enhancing rice yields. Additionally, reducing relative humidity can positively impact the microclimate, thereby reducing the susceptibility of rice crops to pests and diseases. However, increased maximum temperature, particularly during flowering, adversely influences rice yield. Additionally, a fall in minimum temperature between 15 °C to 18 °C during early November negatively impacts seed germination in nurseries. The time trend variable is significant ($p < 0.00$), indicating that advancements in technology, such as improved varieties, better seed, agronomic practices, and plant protection measures, have contributed to increased rice yields over time. The interaction between rainfall and maximum temperature showed positive and significant associated with mean yield. Among the four district dummies, Krishna and West Godavari districts showed a positive influence on mean yield compared to the benchmark district, Kurnool. However, in Cobb-Douglas model, Chittoor district also exhibits significant influence.

Table 7. Estimates of Just and Pope function during Rabi season.

S.No	Variables	Quadratic model				Cobb-Douglas model			
		Mean Yield		Yield Variability		Mean Yield		Yield Variability	
		Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
1	Rainfall	0.0321**	0.0093	−0.0035**	0.0007	1.8783**	0.5126	−0.3167**	0.1029
2	Max.Temp	−0.0018**	0.0003	0.0017**	0.0004	−0.0003**	0.0001	0.0195**	0.0061
3	Min.Temp	−0.0042**	0.0004	0.0026**	0.0008	−0.0004**	0.0001	0.0129**	0.0041
4	Time trend	0.1266**	0.0294	0.3313**	0.0691	0.1069**	0.0258	0.3208**	0.0846
5	$Rain^2$	−0.0003	0.0021	0.0004	0.0011	-	-	-	-
6	$Max.Temp^2$	−0.2137	0.0215	0.0626	0.1593	-	-	-	-
7	$Min.Temp^2$	−0.0004**	0.0001	0.0052**	0.0008	-	-	-	-
8	Rain*Max.Temp	0.0012**	0.0004	0.0022	0.0024	0.2234*	0.0974	−0.0031	0.0058
9	Rain*Min.Temp	0.0002	0.0002	−0.0017	0.0011	0.1729	0.3324	8.4964	5.7082
10	Max.Temp * Min.Temp	0.0212	0.0276	0.0256	0.1678	0.0157	7.1752	−8.6340	7.3043
11	D2-Chittoor	−0.1885	0.1579			−0.2064*	0.0881		
12	D3-Srikakulam	0.2537	0.1918			−0.0672	0.0658		
13	D4-Krishna	0.1609**	0.0435			0.0327**	0.0051		
14	D5-West Godavari	0.6994**	0.1739			0.2970**	0.0577		
	Constant	232.7963	31.8768	28.6526	4.0067	3.7442	80.1436	50.955	9.5342
	Model statistics								
	Observations (n)	125		125		125		125	
	F test (14, 110)	61.88**		F(14, 110) = 2.06*		F test (11, 113) = 14.77**		F(11, 113) = 2.71**	
	Prob > F	0.0000		0.0211		0.0000		0.0048	
	R^2 Adj	0.8959				0.6047			

Note: ** - Significant at 1% level, * - Significant at 5% level

In the quadratic model, quadratic term for minimum temperature exerted a significant negative influence on mean yield, implying that below a threshold level, minimum temperature adversely affects the mean yield. This finding aligns with the results of Joshi et al. (2011), indicating that lower minimum temperatures during the Rabi season exerted a negative impact on rice yield. The quadratic term of rainfall, although non-significant, exerts a negative influence on mean yield if it leads to submergence for more than a week during crop growth. According to Peng et al. (2004), even minor increases in night temperatures can adversely affect the yield of irrigated rice during the Rabi season, indicating the potentially detrimental impact of higher night temperatures on rice yield. These findings underscore the significance of recognizing temperature thresholds and acknowledging the adverse effects of excessive rainfall and elevated night temperatures on rice yield during the Rabi season. Moreover, the findings align with those of Chandio et al. (2021; 2022a; 2022e; 2023) in various regions such as Pakistan, Asian-7 countries, China, and South Asia, as well as the study by Chandio et al. (2022c) in SAARC countries.

In terms of yield variability, both the quadratic and Cobb-Douglas models identify rainfall as a risk-mitigating factor, suggesting that higher levels of rainfall contribute to lower yield variability, unlike maximum and minimum temperatures. Additionally, time trend is associated with increased yield variability likely due to various factors such as shifting climate patterns, evolving agricultural practices, and technological progress. Notably, in the quadratic model, the squared minimum temperature emerges as a risk-increasing factor for rice yield. These findings underscore the importance of adequate rainfall, optimal temperature conditions, and ongoing technological advancements in reducing yield variability and bolstering the stability of rice production.

The differential impact of temperature on rice yield between the Kharif and Rabi seasons can be attributed to several agronomic and climatic factors, suggesting potential threshold effects. The Kharif season, characterized by the monsoon, presents optimal conditions for rice growth, as higher temperatures combined with abundant rainfall promote photosynthesis and plant development. During this season, rice plants benefit from maximum temperatures that remain below a critical threshold of approximately 35–40 °C; exceeding this limit can induce heat stress, adversely affecting yields. In contrast, the Rabi season features cooler and drier weather, which may slow down metabolic processes and affect plant development. Cooler temperatures are generally favorable for germination and early growth, with a critical threshold for minimum temperatures. Specifically, temperatures below 15 °C can hinder germination and seedling vigor, while the optimal range is between 18–25 °C. If temperatures drop significantly below these levels, especially at night, growth can be stunted, leading to reduced yields. Additionally, the risk of frost in colder regions can further compromise young rice plants. The photoperiod sensitivity of rice also plays a role in this differential impact. During the Kharif season, longer days and warmer temperatures enhance growth, while the shorter days of the Rabi season may not have the same beneficial effect. Moreover, the interaction between temperature and other climatic factors, particularly rainfall, is crucial. Adequate moisture during the Kharif season can help mitigate the negative effects of elevated temperatures, emphasizing the importance of rainfall in conjunction with temperature.

The significant time trend variable observed in the analysis underscores the impact of various technological advancements on rice yield over time. Key improvements include the development of high-yielding varieties (HYVs) and hybrid rice strains that enhance productivity, disease resistance, and adaptability to varying climatic conditions. Precision agriculture techniques, such as satellite imagery and soil moisture sensors, allow farmers to optimize irrigation, fertilization, and pest management, maximizing resource efficiency and minimizing waste. Innovations in water management, including drip irrigation and rainwater harvesting, ensure adequate moisture supply, particularly during critical growth stages, while reducing reliance on unpredictable rainfall patterns. Integrated pest management (IPM) strategies combine biological, cultural, and chemical control methods to reduce crop losses from pests and diseases. Additionally, practices that enhance soil health, such as organic amendments and cover cropping, improve soil fertility and structure, promoting better root development and nutrient uptake. Agricultural mechanization has also increased operational efficiency, allowed timely planting and harvesting. These advancements not only boost yields but also interact with climate change by enhancing resilience; for example, HYVs resilient to temperature extremes help mitigate climate impacts. Precision agriculture optimizes inputs based on real-time data, aiding adaptation to climate variability. However, intensive use of chemicals can lead to soil degradation and water pollution, posing sustainability challenges. Overall, integrating these technological innovations enhances rice yields and plays a vital role in adapting to climate change, highlighting the need for ongoing research and sustainable practices to ensure long-term production stability.

4.3.3. Elasticities (Marginal effects) of Climate Variables

According to Table 8, both the Quadratic and Cobb-Douglas models reveal positive associations between rainfall, maximum and minimum temperatures with mean rice yield during the Kharif season. The reported elasticities denote the percentage change in rice yield resulting from a one percent change in the respective climate variables. Specifically, for rainfall, the elasticities range from 0.837 to 0.914. This signifies that a one percent increase in rainfall corresponds to an average increase in rice yield by approximately 0.837 to 0.914 percent. Hence, higher rainfall positively affects rice yield during the Kharif season. Regarding maximum temperature, elasticities range from 0.035 to 0.042 implying that one percent rise in maximum temperature corresponds to an average increase in rice yield by approximately 0.035 to 0.042 percent. Thus, higher maximum temperatures also have a positive influence on rice yield during the Kharif season. Similarly, for minimum temperature, the elasticities range from 0.025 to 0.032. Hence, higher minimum temperatures contribute to higher rice yields during the Kharif season. Furthermore, these climate change variables—rainfall, maximum temperature, and minimum temperature—also exhibit risk-decreasing characteristics with elasticities of 0.752 to 0.819 percent, 0.052 to 0.055 percent, and 0.001 to 0.005 percent, respectively. So, these variables play a role in alleviating the risk and uncertainty inherent in rice yield, thereby fostering more steady and reliable production. Moreover, these variables serve as risk-mitigating factors, bolstering the resilience of rice production amidst the backdrop of climate change (Kim & Pang, 2009).

Table 8. Elasticities of climate change variables.

Yield function	Climate variables	Quadratic model	Cobb-Douglas model
Kharif season			
	Rainfall	0.8371	0.9143
Mean yield	Maximum Temperature	0.0424	0.0353
	Minimum Temperature	0.0325	0.0251
	Rainfall	−0.7516	−0.8199
Yield variability	Maximum Temperature	−0.0546	−0.0519
	Minimum Temperature	−0.0049	−0.0011
Rabi season			
	Rainfall	1.9447	1.8783
Mean yield	Maximum Temperature	−0.0002	−0.0003
	Minimum Temperature	−0.0008	−0.0004
	Rainfall	−0.2120	−0.3167
Yield variability	Maximum Temperature	0.0136	0.0195
	Minimum Temperature	0.0143	0.0129

However, during Rabi season, for Quadratic and Cobb-Douglas models, only rainfall exhibits a positive association with mean yield with elasticities ranging between 1.878 to 1.945 percent. However, the elasticities for maximum temperature ranged between −0.0002 to −0.0003, while the elasticities for minimum temperature ranged between −0.0004 to −0.0008. So, a one percent rise in maximum temperature or minimum temperature corresponds to an average decrease in rice yield by approximately 0.0002 to 0.0003 percent and 0.0004 to 0.0008 percent, respectively. The reported elasticities for yield variability ranged between 0.014 to 0.019 percent, and 0.013 to 0.014 percent with respect to maximum and minimum temperatures respectively. On the contrary, the elasticities are considerably lower for rainfall ranging between −0.212 to −0.317 percent implying that higher rainfall reduces yield variability.

The robustness and reliability of the model used in this study were ensured through several methods, despite the absence of explicit out-of-sample tests. The analysis employed both quadratic and Cobb-Douglas functional forms to capture the nonlinear and interactive effects of climate variables—rainfall, maximum temperature, and minimum temperature—on rice yields. The consistency of results across these two models provided an initial indication of robustness, especially as both models revealed similar trends and significance for key variables, including potential threshold effects identified by the quadratic model. Additionally, the estimated elasticities of climate variables showed consistent effects on rice yields, aligning with previous studies conducted in comparable agro-climatic contexts (e.g., Isik & Devadoss, 2006; Sarker et al., 2014). This alignment with prior research was further reinforced by the inclusion of significant time trend variables and district dummies, which accounted for technological advancements in rice cultivation and regional differences in yield. Residual analysis and diagnostic tests for heteroscedasticity and autocorrelation were conducted to ensure the internal consistency of the models, thus bolstering their reliability. Although out-of-sample validation was not performed, the comprehensive historical dataset spanning from 1998 to 2022 provided a sufficiently broad foundation for estimating reliable relationships between climate variables and rice yield. This multifaceted approach to model validation enhances confidence in the findings' applicability and reliability, showcasing a well-rounded methodology for assessing the impact of climate on rice production.

4.3.4. Effects of Future Climate Change

In Kharif season, projected rice yields (Table 9) are expected to increase by 28.29 percent (quadratic model) and 25.66 percent (Cobb-Douglas model) by the year 2080. The quadratic model predicts a higher increase in mean yield over the Cobb-Douglas model. This led to a reduction in yield variability for rice (quadratic and Cobb-Douglas) over the selected four periods. Interestingly, a decrease in yield variability is observed to increase over time and is higher in the quadratic model compared to the Cobb-Douglas model (Kabir, 2015). In Rabi season, the projected rice yields are expected to increase by 23.08 percent (quadratic model) and 22.36 percent (Cobb-Douglas model) by the year 2080. However, it is noted that yield variability is projected to slightly increase over four periods, albeit at a slow increasing rate. So, climate change showed a positive impact on rice yields, with higher projected increases in the quadratic model. Additionally, the study highlights a decrease in yield variability over time, indicating a potentially more stable rice production system in the future.

Table 9. Projected change for rice yields during 2030, 2040, 2050, and 2080.

Years & Climate projections*	Quadratic Model		Cobb-Douglas model	
	Mean Yield (%)	Yield Variability (%)	Mean Yield (%)	Yield Variability (%)
Kharif season				
2030 [ΔR = 5%; ΔMaxT = 1.26 ˚C; ΔMint = 1.36 ˚C]	13.94	−11.30	12.43	−10.789
2040* [ΔR = 7%; ΔMaxT = 1.50 ˚C; ΔMint = 1.75 ˚C]	17.90	−14.30	16.09	−13.717
2050 [ΔR = 10%;ΔMaxT = 1.81 ˚C; ΔMint = 2.14 ˚C]	22.99	−18.44	20.90	−17.828
2080 [ΔR = 12%;ΔMaxT = 2.29 ˚C; ΔMint = 2.63 ˚C]	28.29	−22.80	25.66	−22.013
Rabi season				
2030 [ΔR = 5%; ΔMaxT = 1.26 ˚C; ΔMint = 1.36 ˚C]	9.59	2.60	9.30	2.62
2040* [ΔR = 7%; ΔMaxT = 1.50 ˚C; ΔMint = 1.75 ˚C]	13.45	3.06	13.03	2.96
2050 [ΔR = 10%;ΔMaxT = 1.81 ˚C; ΔMint = 2.14 ˚C]	19.24	3.40	18.64	3.11
2080 [ΔR = 12%;ΔMaxT = 2.29 ˚C; ΔMint = 2.63 ˚C]	23.08	4.33	22.36	4.04

*- Singh et al., 2020

The statistical findings underscore the critical role that rainfall and temperature play in influencing rice yield during both the Kharif and Rabi seasons, with significant implications for farmers and policymakers aiming to enhance agricultural resilience in the face of climate change. For farmers, understanding the positive impact of adequate rainfall and optimal temperature ranges on rice yields enables them to adopt more effective cultivation practices. For instance, investing in water management techniques, such as rainwater harvesting and efficient irrigation systems, can help ensure sufficient moisture availability during crucial growth stages, particularly in the Kharif season, where rainfall significantly enhances yield. Moreover, farmers can implement heat-resilient rice varieties that are better adapted to withstand temperature extremes, particularly during the Rabi season, when lower minimum temperatures can impede seed germination.

Policymakers, on the other hand, can leverage these insights to formulate targeted support programs that promote the adoption of sustainable agricultural practices and technologies. Initiatives could include providing training and resources on climate-smart agriculture, facilitating access to high-yielding and climate-resilient rice varieties, and improving agricultural extension services to disseminate information on best practices. Additionally, establishing local agricultural cooperatives can help farmers share knowledge, access shared resources, and implement collective water management strategies. Enhancing local infrastructure for storage and transport can also mitigate post-harvest losses and improve market access, enabling farmers to maximize the benefits of favorable climatic conditions. Ultimately, these adaptation strategies will not only bolster rice production but also contribute to broader food security goals in the context of a changing climate, ensuring that agricultural practices remain viable and sustainable for future generations.

The findings from this study align with and contrast with various global studies examining the impact of climate variables on rice yields. For instance, studies in India, such as those by Kumar et al. (2015) and Srivastava et al. (2019), have similarly identified significant relationships between rainfall and temperature on rice productivity, highlighting the critical role of these climatic factors in influencing yields during both Kharif and Rabi seasons. Moreover, the threshold effects noted in this study, particularly the detrimental impacts of excessive rainfall and high maximum temperatures, corroborate the findings of research conducted in other rice-growing regions, such as the Philippines and China, where adverse climate conditions have been shown to negatively affect rice yields (Stuecker et al., 2018; Saud et al, 2022). Globally, the variability in rice yield due to climatic factors has been extensively documented, with studies indicating that higher temperatures can substantially affect growth stages, particularly during flowering (Li & Tao, 2023). For example, the findings regarding the negative influence of elevated minimum temperatures during the Rabi season echo concerns raised in the literature highlighting the importance of optimal temperature ranges for effective rice germination and growth. Additionally, the beneficial impact of technological advancements, as indicated by the significant time trend variable, resonates with global initiatives aimed at improving rice yield through innovation and adaptive practices in the face of climate change, such as the development of heat-tolerant varieties (Hollósy et al., 2023). However, while some studies emphasize the direct effects of climate change on yield reductions, the nuanced findings of this study, particularly concerning the risk-mitigating role of rainfall and temperature interactions, suggest a complex interplay between climatic variables that requires further investigation and targeted agronomic strategies to enhance resilience in rice production systems globally.

5. Conclusions and Suggestions

This study showed climate change has significant implications for rice yields in selected agro-climatic regions of Andhra Pradesh. The selected districts represent different agro-climatic zones, accounting for a significant proportion of rice cultivation. Historical climate data, including rainfall and temperature, were collected during 1998–2022, along with corresponding rice yield data. Unit root tests conducted ensured that the data were stationary. The findings indicate that Srikakulam district received the highest mean rainfall during the Kharif season, followed by West Godavari and Krishna districts. On the other hand, Kadapa and Kurnool districts in the dry Rayalaseema region received the lowest mean rainfall. In terms of rice yields, Kurnool district had the highest variability, followed by Kadapa. In contrast, the three coastal districts—Srikakulam, West Godavari, and Krishna—exhibited lower yield variability, attributed to the presence of perennial rivers. Notably, Chittoor district in the Rayalaseema region recorded the highest mean rainfall during the Rabi season, coupled with the lowest variability. This phenomenon is attributed to Chittoor receiving rainfall from the northeast and retreating monsoons during the winter season. Moreover, the Rabi rice yield variability was observed to be higher in coastal districts compared to Kharif season. Additionally, maximum and minimum temperatures registered higher levels during the Rabi season relative to Kharif season. Krishna district demonstrated the highest rice productivity in the Kharif season, whereas Srikakulam reported the lowest. Conversely, during the Rabi season, rice productivity surged across all three coastal districts in comparison to the Kharif season. Pre-estimation specification tests affirmed the stationarity of the climate change variables and rice yields. Furthermore, tests for heteroscedasticity, autocorrelation, and contemporaneous correlation were conducted, lending support for the application of the Just-Pope model. Findings from this model unveiled that rainfall, maximum temperature, and minimum temperature significantly influenced the mean yield of rice across both seasons. Moreover, the time trend variable, indicative of technological progress, exhibited a positive influence on rice yield. Regarding yield variability, rainfall, maximum temperature, and minimum temperature are considered as variance-decreasing factors. The rainfall elasticity ranges from 0.837 to 0.914 during Kharif season. Maximum temperature elasticity ranges from 0.035 to 0.042, and minimum temperature elasticity ranges from 0.025 to 0.032. These variables also reduce yield variability by approximately 0.752 to 0.819 percent, 0.052 to 0.055 percent, and 0.001 to 0.005 percent, respectively, mitigating production risks and enhancing stability amidst climate change. In Rabi season, rainfall exhibits a positive association with mean rice yield, with elasticities ranging from 1.878 to 1.945 percent per one percent increase. However, maximum temperature and minimum temperature showed negative associations, with elasticities ranging between −0.0002 to −0.0003 and −0.0004 to −0.0008 percent, respectively. These variables also increase yield variability by approximately 0.014 to 0.019 percent and 0.013 to 0.014 percent, respectively. In contrast, rainfall decreases yield variability by approximately 0.212 to 0.317 percent. In future, rice yields would increase both in Kharif and Rabi seasons by 2080. However, yield variability would slightly increase in the Rabi season, while decreasing in the Kharif season over time.

These findings emphasize directing research efforts towards the development of new cultivars that are capable of tolerating multiple biotic and abiotic stresses, rather than focusing on a limited number of stresses. Increasing access of farmers to agro-meteorological information will help farmers make informed choices and adopt sustainable practices in rice production in Andhra Pradesh. Additionally, the research highlights the significance of collecting reliable climate data and ensuring regular updates in the study area. Accurate and up-to-date climate data are crucial for conducting effective research, monitoring climate patterns, and planning adaptation strategies. In view of these findings, farmers can mitigate risks associated with climate variability in rice cultivation by adopting a multifaceted approach centered on climate-smart agricultural practices. Key strategies include crop diversification, such as intercropping with drought-resistant crops during the Kharif season and transitioning to resilient crops like pulses and oilseeds in the Rabi season. Improved water management practices, such as rainwater harvesting and the use of efficient irrigation systems like drip or sprinkler irrigation, are essential for optimizing water use in water-scarce regions. Additionally, enhancing soil health through organic amendments and cover crops will boost fertility and moisture retention, while the adoption of climate-resilient rice varieties tolerant to heat and drought is crucial. Access to agro-meteorological information via mobile apps and local weather stations will empower farmers to make informed decisions. Policymakers can support these efforts by investing in research for resilient rice varieties, enhancing agro-meteorological services, and providing financial incentives for adopting sustainable practices. Furthermore, investing in rural infrastructure, facilitating workshops on sustainable farming, and establishing collaborative frameworks among agricultural stakeholders will foster resilience in the sector. Ongoing monitoring and evaluation of climate impacts on rice production will enable adaptive management strategies, ultimately contributing to food security in Andhra Pradesh.

This study identifies several limitations, particularly regarding data constraints and model assumptions. One significant limitation is the omission of non-climate variables, such as edaphic conditions, cropped area, irrigation practices, fertilizer application, adoption of high-yielding variety seeds, and occurrences of extreme natural events, in the Just-Pope production function. This omission may result in an incomplete understanding of rice production dynamics and yield variability, as these factors can significantly influence agricultural outcomes. Additionally, the reliance on historical climate data (1998–2022) may not adequately capture the rapidly changing climate conditions and their impacts on rice yields, potentially affecting the robustness of the findings. This study also acknowledges a limitation in its approach by not incorporating non-climate variables (such as edaphic conditions, cropped area, irrigation practices, fertilizer application, adoption of high-yielding variety seeds, and occurrences of extreme natural events) into the utilized Just and Pope production function. By omitting these variables, the findings may offer an incomplete understanding of rice production dynamics and yield variability. Integrating such variables into the production function would facilitate a more comprehensive analysis, enabling a nuanced assessment of their individual contributions to production risk and yield outcomes. Previous research, as evidenced by studies conducted by Guttormsen and Roll (2013), Rosegrant and Roumasset (1985), Roumasset et al. (1989), Ramaswami (1992), and Di Falco et al. (2006), underscores the significance of non-climate variables in agricultural production, including rice cultivation. Thus, future studies stand to benefit from incorporating these variables, thereby fostering a more accurate comprehension of the multifaceted dynamics influencing rice production.

Future research should aim to address these limitations by incorporating a broader range of climate variables, such as humidity and wind speed, which can further elucidate the impacts of climate change on rice cultivation. Exploring the interactions between multiple climate factors and their cumulative effects on yields could enhance the comprehensiveness of the analysis. Furthermore, expanding the scope of research to include other crops affected by climate change, such as pulses, oilseeds, or vegetables, would provide valuable insights into the resilience of various agricultural systems. Investigating the role of adaptive management practices and technological innovations in mitigating climate risks will also be crucial in developing effective strategies for sustainable agricultural production in the face of ongoing climate challenges.

CRediT Author Statement: Kotamraju Nirmal Ravi Kumar: Conceptualization, Methodology and Writing initial draft; **Tatineni Ramesh Babu:** Expert suggestions; **Adinan Bahahudeen Shafiwu:** Expert suggestions; **Kavanadala Rangaraju Hamsa:** Analysis of data; **Ishaque Mahama:** Analysis of data and editing.

Data Availability Statement: Not applicable

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgments: Not applicable.

References

Baig, I. A., Chandio, A. A., Ozturk, I., Kumar, P., Khan, Z. A., & Salam, M. A. (2022). Assessing the long- and short-run asymmetrical effects of climate change on rice production: Empirical evidence from India. *Environmental Science and Pollution Research*, *29*, 34209–34230. https://doi.org/10.1007/s11356-021-18014-z

Barnwal, P., & Kotani, K. (2010). *Impact of variation in climate factors on crop yield: A case of rice crop in Andhra Pradesh, India*. Economics & Management Series. https://iuj.repo.nii.ac.jp/records/435

Cabas, J., Weersink, A., & Olale, E. (2010). Crop yield response to economic, site and climatic variables. *Climatic Change*, *101*, 599–616. https://doi.org/10.1007/s10584-009-9754-4

Cameron, A. C., & Trivedi, P. K. (2009). *Microeconometrics using stata*. Stata Press.

Carew, R., Meng, T., Florkowski, W. J., Smith, R., & Blair, D. (2017). Climate change impacts on hard red spring wheat yield and production risk: Evidence from Manitoba, Canada. *Canadian Journal of Plant Science*, *98*(3), 782–795. https://doi.org/10.1139/cjps-2017-0135

Chandio, A. A., Akram, W., Sargani, G. R., Twumasi, M. A., & Ahmad, F. (2022a). Assessing the impacts of meteorological factors on soybean production in China: What role can agricultural subsidy play? *Ecological Informatics*, *71*, 101778. https://doi.org/10.1016/j.ecoinf.2022.101778

Chandio, A. A., Gokmenoglu, K. K., Ahmad, F., & Li, J. (2022c). Towards sustainable agriculture in SAARC countries: Exploring the long-run impact of GHG emissions on agricultural productivity. *International Journal of Environmental Science and Technology*, *20*, 10049–10060. https://doi.org/10.1007/s13762-022-04582-1

Chandio, A. A., Gokmenoglu, K. K., Ahmad, M., & Jiang, Y. (2022d). Towards sustainable rice production in Asia: The role of climatic factors. *Earth System and Environment*, *6*, 1–14. https://doi.org/10.1007/s41748-021-00210-z

Chandio, A. A., Jiang, Y., Akram, W., Adeel, S., Irfan, M., & Jan, I. (2021). Addressing the effect of climate change in the framework of financial and technological development on cereal production in Pakistan. *Journal of Cleaner Production*, *288*, 125637. https://doi.org/10.1016/j.jclepro.2020.125637

Chandio, A. A., Jiang, Y., Amin, A., Akram, W., Ozturk, I., Sinha, A., & Ahamd, F. (2022b). Modeling the impact of climatic and non-climatic factors on cereal production: Evidence from Indian agricultural sector. *Environmental Science and Pollution Research*, *29*, 14634–14653. https://doi.org/10.1007/s11356-021-16751-9

Chandio, A. A., Jiang, Y., Amin, A., Ahmad, M., Akram, W., & Ahmad, F. (2023). Climate change and food security of South Asia: Fresh evidence from a policy perspective using novel empirical analysis. *Journal of Environmental Planning and Management*, *66*(1), 169–190. https://doi.org/10.1080/09640568.2021.1980378

Chandio, A. A., Sethi, N., Dash, D. P., & Usman, M. (2022e). Towards sustainable food production: What role ICT and technological development can play for cereal production in Asian–7 countries? *Computers and Electronics in Agriculture*, *202*, 107368. https://doi.org/10.1016/j.compag.2022.107368

Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G., & Ravindranath, N. H. (2012). Multi-model climate change projections for India under representative concentration pathways. *Current Science*, *103*(7), 791–802. http://www.jstor.org/stable/24088836

Chen, C. C., & Chang, C. C. (2005). The impact of weather on crop yield distribution in Taiwan: Some new evidence from panel data models and implications for crop insurance. *Agricultural Economics, 33*(s3), 503–511. https://doi.org/10.1111/j.1574-0864.2005.00097.x

Chen, C. C., McCarl, B. A., & Schimmelpfennig, D. E. (2004). Yield variability as influenced by climate: A statistical investigation. *Climatic Change, 66*, 239–261. https://doi.org/10.1023/B:CLIM.0000043159.33816.e5

Di Falco, S., Chavas, J. P., & Smale, M. (2007). Farmer management of production risk on degraded lands: The role of wheat genetic diversity in Tigray region, Ethiopia. *Agricultural Economics*, *36*(2), 147–156. https://doi.org/10.1111/j.1574-0862.2007.00194.x

Directorate of Economics and Statistics. (2022). *Agricultural Statistics at a Glance 2020*. Government of India, Ministry of Agriculture & Farmers Welfare, Department of Agriculture, Cooperation & Farmers Welfare. https://desagri.gov.in/wp-content/uploads/2021/09/At-a-Glance-2020-Eng.pdf

Gadedjisso-Tossou, A., Adjegan, K. I., & Kablan, A. K. M. (2021). Rainfall and temperature trend analysis by Mann–Kendall test and significance for rainfed cereal yields in Northern Togo. *Sci*, *3*(1), 17. https://doi.org/10.3390/sci3010017

Gbetibouo, G. A., & Hassan, R. M. (2005). Measuring the economic impact of climate change on major South African field crops: A Ricardian approach. *Global and Planetary Change*, *47*(2–4), 143–152. https://doi.org/10.1016/j.gloplacha.2004.10.009

Granger, C. W. J., & Newbold, P. (1974). Spurious regressions in econometrics. *Journal of Econometrics*, *2*(2), 111–120. https://doi.org/10.1016/0304-4076(74)90034-7

Gupta, R., & Mishra, A. (2019). Climate change induced impact and uncertainty of rice yield of agro-ecological zones of India. *Agricultural Systems*, *173*, 1–11. https://doi.org/10.1016/j.agsy.2019.01.009

Guttormsen, A. G., & Roll, K. H. (2013). Production risk in a subsistence agriculture. *The Journal of Agricultural Education and Extension*, *20*(1), 133–145. https://doi.org/10.1080/1389224X.2013.775953

Harris, R. D. F., & Tzavalis, E. (1999). Inference for unit roots in dynamic panels where the time dimension is fixed. *Journal of Econometrics*, *91*(2), 201–226. https://doi.org/10.1016/S0304-4076(98)00076-1

Hollósy, Z., Ma'ruf, M. I., & Bacsi, Z. (2023). Technological advancements and the changing face of crop yield stability in Asia. *Economies*, *11*(12), 297. https://doi.org/10.3390/economies11120297

Isik, M., & Devadoss, S. (2006). An analysis of the impact of climate change on crop yields and yield variability. *Applied Economics*, *38*(7), 835–844. https://doi.org/10.1080/00036840500193682

Joshi, N. P., Maharjan, K. L., & Piya, L. (2011). Effect of climate variables on yield of major food-crops in Nepal -A time-series analysis-. *Journal of Contemporary India Studies: Space and Society*, *1*, 19–26. https://mpra.ub.uni-muenchen.de/35379/

Judge, G. G., Griffiths, W. E., Hill, R. C., Lütkepohl, H., & Lee, T. C. (1985). *The theory and practice of econometrics* (2nd ed.). John Wiley & Sons.

Just, R. E., & Pope, R. D. (1978). Stochastic specification of production functions and economic implications. *Journal of Econometrics*, *7*(1), 67–86. https://doi.org/10.1016/0304-4076(78)90006-4

Just, R. E., & Pope, R. D. (1979). Production function estimation and related risk considerations. *American Journal of Agricultural Economics*, *61*(2), 276–284. https://doi.org/10.2307/1239732

Kabir, H. (2015). Impacts of climate change on rice yield and variability; an analysis of disaggregate level in the southwestern part of Bangladesh especially Jessore and Sathkhira Districts. *Journal of Geography and Natural Disaster*, *5*, 3.

https://www.longdom.org/open-access/impacts-of-climate-change-on-rice-yield-and-variability-an-analysis-ofdisaggregate-level-in-the-southwestern-part-of-bangladesh-especially-2167-0587-1000148.pdf
Kim, M. K., & Pang, A. (2009). Climate change impact on rice yield and production risk. *Journal of Rural Development*, *32*(2), 17–29. https://doi.org/10.22004/ag.econ.90682
Koundouri, P., & Nauges, C. (2005). On production function estimation with selectivity and risk considerations. *Journal of Agricultural and Resource Economics*, *30*(3), 597–608. https://doi.org/10.22004/ag.econ.30977
Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A., & Chakraborty, S. (2020). *Assessment of climate change over the Indian Region: A report of the Ministry of Earth Sciences (MoES), Government of India.* Springer Singapore. https://doi.org/10.1007/978-981-15-4327-2
Kumar, A., Sharma, P., & Ambrammal S. K. (2015). Effects of climatic factors on productivity of cash crops in India: Evidence from state-wise panel data. *Global Journal of Research in Social Sciences*, *1*(1), 9–18. https://www.researchgate.net/publication/344317299
Kumbhakar, S. C., & Tveteras, R. (2003). Risk preferences, production risk, and firm heterogeneity. *The Scandinavian Journal of Economics*, *105*(2), 275–293. https://doi.org/10.1111/1467-9442.t01-1-00009
Li, Y., & Tao, F. (2023). Rice yield response to climate variability diverges strongly among climate zones across China and is sensitive to trait variation. *Field Crops Research*, *301*, 109034. https://doi.org/10.1016/j.fcr.2023.109034
Maddala, G. S., & Wu, S. (1999). A comparative study of unit root tests with panel data and a new simple test. *Oxford Bulletin of Economics and Statistics*, *61*(S1), 631–652. https://doi.org/10.1111/1468-0084.61.s1.13
Mandal, R., & Singha, P. (2020). Impact of climate change on average yields and their variability of the principal crops in Assam. *Indian Journal of Agricultural Economics*, *75*(3), 305–316. https://isaeindia.org/wp-content/uploads/2020/11/03-Article-Raju-Mandal.pdf
McCarl, B. A., Villavicencio, X., & Wu, X. (2008). Climate change and future analysis: Is stationary dying? *American Journal of Agricultural Economics*, *90*(5), 1241–1247. https://doi.org/10.1111/j.1467-8276.2008.01211.x
Mendelsohn, R., & Williams, L. (2004). Comparing forecasts of the global impacts of climate change. *Mitigation and Adaptation Strategies for Global Change*, *9*, 315–333. https://doi.org/10.1023/B:MITI.0000038842.35787.1d
Mulungu, K., Tembo, G., Bett, H., & Ngoma, H. (2021). Climate change and crop yields in Zambia: Historical effects and future projections. *Environment, Development and Sustainability*, 11859–11880. https://doi.org/10.1007/s10668-020-01146-6
Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., Centeno, G. S., Khush, G. S., & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceeding of the National Academy Sciences*, *101*(27), 9971–9975. https://doi.org/10.1073/pnas.0403720101
Poudel, S., & Kotani, K. (2013). Climatic impacts on crop yield and its variability in Nepal: Do they vary across seasons and altitudes? *Climatic Change*, *116*, 327–355. https://doi.org/10.1007/s10584-012-0491-8
Ramaswami, B. (1992). Production risk and optimal input decisions. *American Journal of Agricultural Economics*, *74*(4), 860–869. https://doi.org/10.2307/1243183
Rao, C. A. R., Raju, B. M. K., Rao, A. V. M. S., Rao, K. V., Rao, V. U. M., Ramachandran, K., Venkateswarlu, B., Sikka, A. K., Rao, M. S., Maheswari, M., & Rao, C. S. (2016). A district level assessment of vulnerability of Indian agriculture to climate change. *Current Science*, *110*(10), 1939–1946. https://doi.org/10.18520/cs/v110/i10/1939-1946
Rao, C. A. R., Raju, B. M. K., Rao, A. V. M. S., Rao, K. V., Samuel, J., Ramachandran, K., Nagasree, K., Kumar, R. N., & Shankar, K. R. (2017). Assessing vulnerability and adaptation of agriculture to climate change in Andhra Pradesh. *Indian Journal of Agricultural Economics*, *72*(3), 375–384. http://dx.doi.org/10.22004/ag.econ.302273
Resop, J. P., Fleisher, D. H., Timlin, D. J., & Reddy, V. R. (2014). Biophysical constraints to potential production capacity of potato across the U.S. Eastern Seaboard region. *Agronomy Journal*, *106*(1), 43–56. https://doi.org/10.2134/agronj2013.0277
Rosegrant, M. W., & Roumasset, J. A. (1985). The effect of fertiliser on risk: A heteroscedastic production function with measurable stochastic inputs. *Australian Journal of Agricultural Economics*, *29*(2), 107–121. https://doi.org/10.1111/j.1467-8489.1985.tb00651.x
Saei, M., Mohammadi, H., Ziaee, S., & Dourbash, S. B. (2019). The impact of climate change on grain yield and yield variability in Iran. *Iran Economic Revolution*, *23*(2), 509–531. https://journals.ut.ac.ir/article_70308_fd0c2d2609c8088849e9258ed1f55b1c.pdf
Sanjay, J., Krishnan, R., Ramarao, M. V. S., Mahesh, R., Singh, B. B., Patel, J., Ingle, S., Bhaskar, P., Revadekar, J. V., Sabin, T. P., & Mujumdar, M. (2017). Future climate change projections over the Indian region. arXiv. https://doi.org/10.48550/arXiv.2012.10386
Sarker, M. A. R., Alam, K., & Gow, J. (2014). Assessing the effects of climate change on rice yields: An econometric investigation using Bangladeshi panel data. *Economic Analysis and Policy*, *44*(4), 405–416. https://doi.org/10.1016/j.eap.2014.11.004
Sarker, M. A. R., Alam, K., & Gow, J. (2019). Performance of rain-fed Aman rice yield in Bangladesh in the presence of climate change. *Renewable Agriculture and Food Systems*, *34*(4), 304–312. https://doi.org/10.1017/S1742170517000473
Saud, S., Wang, D., Fahad, S., Alharby, H. F., Bamagoos, A. A., Mjrashi, A., Alabdallah, N. M., AlZahrani, S. S., AbdElgawad, H., Adnan, M., Sayyed, R. Z., Ali, S., & Hassan, S. (2022). Comprehensive impacts of climate change on rice production and adaptive strategies in China. *Frontiers in Microbiology*, *13*. https://doi.org/10.3389/fmicb.2022.926059
Shayanmehr, S., Henneberry, S. R., Sabouni, M. S., & Foroushani, N. S. (2020). Drought, climate change, and dryland wheat yield response: An econometric approach. *International Journal of Environmental Research and Public Health*, *17*(14), 5264. https://doi.org/10.3390/ijerph17145264
Singh, J., Sahany, S., Singh, K. K., Robock, A., & Xia, L. (2024). Future climate change impacts on rice in Uttar Pradesh, India's most populous agrarian state. *Earth's Future*, *12*(5), Article e2023EF004009. https://doi.org/10.1029/2023EF004009
Singh, S., Singh, A., & Nayak, S. (2020). Future climate change impacts on crop productivity in coastal regions of India: A panel estimation. *Climate Change*, *6*(21), 100–108. https://www.discoveryjournals.org/climate_change/current_issue/v6/n21/A9.pdf
Sinnarong, N., Chen, C. C., McCarl, B., & Tran, B. L. (2019). Estimating the potential effects of climate change on rice production in Thailand. *Paddy and Water Environment*, *17*, 761–769. https://doi.org/10.1007/s10333-019-00755-w
Srivastava, R. K., Talla, A., Swain, D. K., & Panda, R. K. (2019). Quantitative approaches in adaptation strategies to cope with increased temperatures following climate change in potato crop. *Potato Research*, *62*, 175–191. https://doi.org/10.1007/s11540-018-9406-z
Stuecker, M. F., Tigchelaar, M., Kantar, M. B. (2018). Climate variability impacts on rice production in the Philippines. *PLoS ONE*, *13*(8), Article e0201426. https://doi.org/10.1371/journal.pone.0201426
Tveterås, R. (1999). Production risk and productivity growth: Some findings for Norwegian salmon aquaculture. *Journal of Productivity Analysis*, *12*, 161–179. https://doi.org/10.1023/A:1007863314751
Tveterås, R., & Wan, G. H. (2000). Flexible panel data models for risky production technologies with an application to salmon aquaculture. *Econometric Reviews*, *19*(3), 367–389. https://doi.org/10.1080/07474930008800477

Vashisht, B. B., Nigon, T., Mulla, D. J., Rosen, C., Xu, H., Twine, T., & Jalota, S. K. (2015). Adaptation of water and nitrogen management to future climates for sustaining potato yield in Minnesota: Field and simulation study. *Agricultural Water Management*, *152*, 198–206. https://doi.org/10.1016/j.agwat.2015.01.011

Verma, S., Gupta, S., & Sen, P. (2020). *Does climate change make foodgrain yields more unpredictable? Evidence from India*. CESifo Working Paper No. 305. https://doi.org/10.2139/ssrn.3555588

Agricultural & Rural Studies

Article

Land Concentration and Social Progress Decline in Brazilian Amazon Municipalities

Raimundo Fagner Frota Vasconcelos [1], Mário Lúcio Ávila [1], Marcelo Ximenes Aguiar Bizerril [1,*], Tamiel Khan Baiocchi Jacobson [1] and Marcelo Mateus Trevisan [1]

1 Center for Management and Innovation of Family Farming, University of Brasilia, Planaltina 73.345-010, Brazil; raimundofagner83@gmail.com (R.F.F.V.); avila@unb.br (M.L.A.); tamiel@unb.br (T.K.B.J.); marcelomtrevisan@gmail.com (M.M.T.)

* Correspondence: bizerril@unb.br

Abstract: Rural populations are directly reliant on ecosystem goods and the land structure within which they are embedded. They are hardship-impacted due to land appropriation and the absence of regulatory mechanisms that ensure sustainable development and socio-environmental conflict prevention. MATOPIBA region encompasses an ecotone area between the Cerrado and Amazon biomes, a significant Brazilian agricultural frontier, and a biodiversity conservation priority area. In this context, we observed an inverse correlation between land concentration and socio-environmental development in ten municipalities in Tocantins State, Brazil. The legal security of land is directly proportional to the Social Progress Index (SPI), which, in turn, is inversely related to land concentration. Therefore, the existence of a multifactorial relationship between SPI, land tenure security, land concentration, and land grabbing should be considered in the development of public policies for land governance and climate change in the Brazilian Amazon region.

Keywords: land tenure security; land grabbing; MATOPIBA; territorial development; rural and traditional populations

1. Introduction

Rural communities in Brazil are marked by the contradictions of the capitalist economic development model. The concentration of land is a long-known phenomenon (Holanda, 2007; Furtado, 2007), and a striking example of this reality. This trend, rooted in the country's colonial history, continues to profoundly influence the current land structure, affecting sustainable development, land use, and the social progress of rural populations (Sant'anna, 2017).

According to França and Marques (2017), Brazil's weak performance in implementing international guidelines, such as those of the Food and Agriculture Organization of the United Nations (2012), highlights the complexity of land governance in the national context. On the other hand, market-based land reform, promoted by the World Bank Group (2014) and criticized by authors such as Sauer and Pereira Leite (2012), illustrates the tensions between a market-based economic development model and the need for more equitable and sustainable policies. The relationship between land tenure and social progress is complex and marked by historical challenges in the Brazilian context, especially regarding land concentration and the legal security of property ownership and registration.

The 1988 Constitution of the Federative Republic of Brazil (1988), in line with UN guidelines, emphasizes the need for a broader debate on access to and use of land that goes beyond economic bias. Article 5 (XXIII) of the Constitution states that land must fulfill its social function, which implies a development approach that values socio-environmental issues. However, recent governments have promoted reforms that have relaxed environmental requirements for access to land, moving away from the demands of popular movements and going against the principles of sustainable development (Sauer et al., 2020; Menezes & Barbosa, 2021). This scenario reflects a development approach focused on the commodification of land, ignoring socio-spatial and environmental complexities.

Indeed, Harvey (1973) argues that geographical space is a social construction, implying that land is more than a physical space, but a space with cultural, social, and economic meanings. Valença (2010) also sees territory as more than just a receptacle for economic processes. Several authors (Smith, 2008; Williamson, 2001; Santos, 2006; Williamson et al., 2010) argue for the need

Citation: Vasconcelos, R. F. F., Ávila, M. L., Bizerril, M. X. A., Jacobson, T. K. B., & Trevisan, M. M. (2025). Land Concentration and Social Progress Decline in Brazilian Amazon Municipalities. *Agricultural & Rural Studies*, *3*(1), 12. https://doi.org/10.59978/ar03010005

Received: 29 October 2024
Revised: 21 November 2024
Accepted: 24 January 2025
Published: 7 March 2025

for a holistic and integrated approach to land administration, which takes into account legal, technical, economic and social aspects, as well as a broader territorial context, recognizing its cultural, social and environmental importance. According to the general systems theory proposed by Bertalanffy and discussed by Dolci et al. (2008), effective territorial development requires an integrated understanding of the relationships among the economic, social, and environmental aspects of land governance. These approaches are corroborated by Sen (1999) who criticizes the hegemonic model of economic development, highlighting the need to consider alternatives that emphasize social well-being and freedom.

Therefore, land governance should not be reduced to a market issue, but understood in a broader context that includes culture, the environment, and social justice. It also should not be seen in isolation but as part of a broader system of territorial development. This system must integrate economic, social, and ecological approaches, recognizing the interdependence between different actors, institutions, and ecosystems. Effective land management is crucial to meeting contemporary challenges and promoting development that is truly inclusive and sustainable.

Thus, in this paper development is understood from the emergence of the last decade and a half in the panorama of development policies based on the territorial approach to rural development (Veiga, 2005). Socio-environmental development is what interests us in this research for the purposes of comparative analysis with land-use planning processes.

The land scenario in the state of Tocantins, located in the MATOPIBA region, is a good place to investigate how land concentration and legal security influence social progress. MATOPIBA is a region comprising the state of Tocantins and parts of Maranhão, Piauí, and Bahia, where agricultural expansion has been strong since the late 1980s, particularly in grain cultivation. The name is formed from the initials of these four states (MA + TO + PI + BA). The interaction between land tenure and social progress in Brazil is a complex and multifaceted issue. Issues related to the concentration and legal security of land tenure have historically been fraught with challenges. Governance, therefore, is not limited to administration per se, but also incorporates citizen participation in the process that concerns communities and socio-environmental sustainability (FAO & Secretaria Especial de Agricultura Familiar e do Desenvolvimento Agrário, 2017).

This article explores these dynamics, analyzing how land concentration and legal land security are reflected in the Social Progress Index (SPI) in the municipalities of Tocantins. The initial hypothesis was that municipalities with greater legal security and lower land concentration would exhibit a higher SPI, suggesting that these factors are crucial for advancing social progress. Through this lens, the study contributes to the debate on rural development, offering a critical perspective on the prevailing economic development model and its implications for land-use planning and social progress.

2. Materials and Methods

2.1. Study Area

Despite being located in the Legal Amazon, the state of Tocantins has around 90% of its original territory occupied by the Cerrado biome. This region, which includes the aforementioned MATOPIBA (Figure 1), is characterized by the expansion of agriculture and the major socio-environmental implications resulting from this scenario (Favareto et al., 2019). This expansion has consequences for the environment and the living conditions of the population, putting the concept of development and social welfare at the center of the debate.

This agricultural frontier has the characteristics of agribusiness in the capitalist mold (Santos, 2020), marked by mechanized agriculture and the incorporation of industrial equipment such as harvesters, planters, biotechnology, and genetic manipulation (Favareto et al., 2019). This technological intensification involves the use of pesticides, fertilizers, and the application of practices aimed at increasing productivity and financial profitability.

Figure 1. Location of the state of Tocantins and the MATOPIBA region in Brazilian territory.

However, the social and internal contradictions of capitalism persist, as Harvey (1973) argues. Tocantins and the Amazon region as a whole are the scene of conflicts between different actors, such as farmers, indigenous people, riverside dwellers, peasants, and quilombolas, as highlighted by the Pastoral Land Commission (Comissão Pastoral da Terra, 2022). These conflicts are directly related to the concentration of land, which perpetuates inequalities and prevents democratic access to natural resources (Pereira & Sauer, 2011).

Figure 2 shows a map illustrating the size and type of each of the main public lands in Tocantins state.

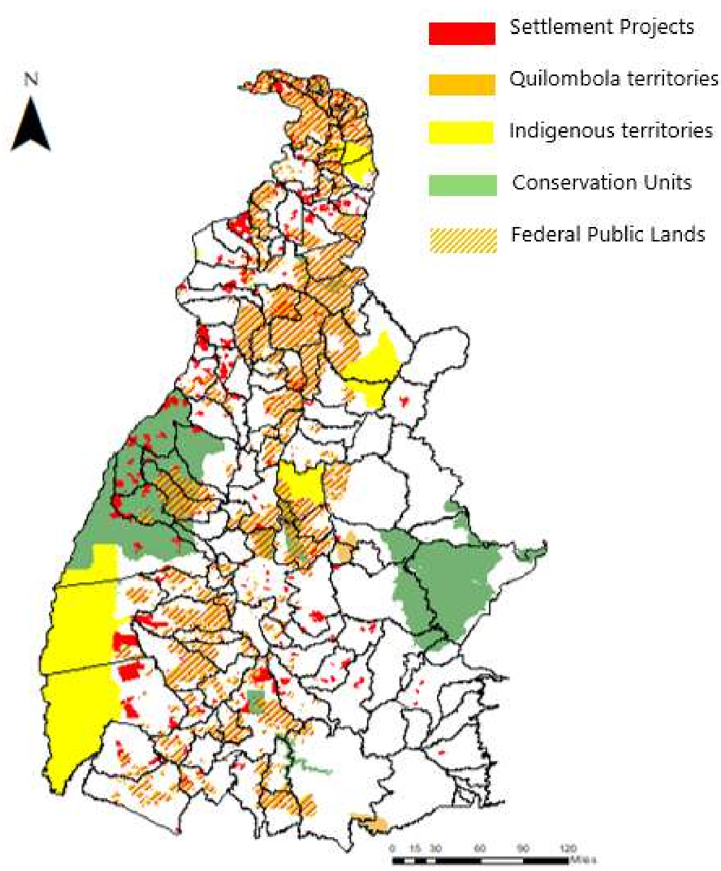


Figure 2. Tocantins' land network.

2.2. Data Collection

We analyzed the relationship between the SPI score for each of the municipalities in the state of Tocantins (highlighting ten municipalities, five with the best and five with the worst performance) and the size of rural properties, following the logic of fiscal modules, to test land concentration by municipality. We also analyzed the relationship between the SPI score and the legal status of the land, characterizing it as possession or ownership.

To analyze the land situation in the municipalities, the database of the Land Collection of the National Institute for Colonization and Agrarian Reform (INCRA; https://acervofundiario.incra.gov.br/acervo/login.php) was used. Data from INCRA's Land Management System (SIGEF) and the National Rural Registration System (SNCR) were used to analyze information on private properties. This data includes Brazil's land ownership structure, such as public lands – Settlement Projects, Conservation Units, Indigenous and Quilombola Territories – as well as data on rural properties.

After collecting the data in shapefile format, the calculations and statistical analysis were carried out using the *ggplot2* package and the dplyr package. The ggplot2 is a system for creating statistical plots and is part of the Tidyverse project's suite of packages. The dplyr package is used for a variety of data analyses, including, but not limited to, biodiversity analysis (Wickham & Grolemund, 2016). It also allowed missing data to be imputed or inconsistent data to be corrected. After this step, the number of records (rows) and variables (columns) was checked and identified, identifying variable names and types.

2.3. Data Analysis and Processing

Initially, a descriptive statistical analysis was carried out on the data collected individually (mean, median, and standard deviation), using the *tidyr* and *ggplot2* packages (*R software*). In order to analyze the land situation of the municipalities based on data from INCRA's Land Collection and correlate possible relationships between the SPI, a bivariate Generalized Linear Models (GLMs) analysis was carried out relating the SPI with the governance of the registers (ratio of the area identified versus the area of the municipality) and with land concentration (size of rural properties in each municipality), as well as the relationship of the SPI with the total area registered in the SNCR and the total area of the municipality, according to IBGE data (https://censoagro2017.ibge.gov.br/).

Scatterplots and cross-tabulations were used to examine the relationship between SPI and these variables with the *ggplot2* package. To assess the statistical significance and strength of these relationships, GLM analysis with a gamma model was applied. Gamma models are a type of generalized regression model used for positive and continuous data, such as rates, times, or quantities. They are particularly useful when data variance increases with the mean, a phenomenon known as heteroscedasticity. The log-link function is commonly used in these models to ensure positive predictions. Gamma models have broad applications in fields such as epidemiology, finance, and ecology, where dependent variables do not follow a normal distribution (McCullagh & Nelder, 1989). After this, multiple dispersion analyses were carried out (*ggplot2* package) where linear regres-sion models were adjusted using the *lm* function.

Multiple linear regression models were used to assess the relationship between the SPI and the variables in INCRA's Land Collection, including the area of public land, as well as the tables in the Agricultural Census and the National Rural Registration System (SNCR). The models were adjusted using the ordinary least squares method and assessed for the quality of the fit based on measures such as the coefficient of determination (R^2) and the residual standard error. These models were adjusted using the maximum likelihood method and assessed for quality of fit using the adjusted coefficient of determination (adjusted R^2) and the residual deviation.

The gamma distribution model was chosen because of the asymmetric and positive distribution of the data. The *gamma* models made it possible to model the variance of the data as a function of the mean, a particularly useful feature when dealing with heteroscedastic data. "Heteroscedastic" refers to the situation in which the error variance is not constant across the values of an independent variable. This contrasts with "homoscedasticity", where the error variance is constant. Models with gamma distribution are useful for addressing heteroscedasticity, as they allow the variance to be modeled as a function of the mean^1^. This step was also carried out using the *R software,* this time using the *MASS* package.

A summary of the analysis steps is shown in Table 1.

Table 1. Study analysis stages.

Stage	Action taken
Loading	Exploratory data analysis: this consisted of loading the tables into the R software, using the readr package to visualize the data;
Cleaning	Missing or inconsistent data was checked and, where necessary, dealt with;
Exploration	Explore the structure of the data, checking the number of records (rows) and variables (columns), the names of these variables and their types;
Univariate analysis	Analysis of individual variables, using tables, frequency graphs and statistical measures such as mean, median and standard deviation, with a view to understanding the distribution and variability of the data;
Bivariate analysis	Analyze the relationship between two variables using scatter plots and cross-tabulations;
Multivariate analysis	Analyze the relationships between three or more variables, using multiple scatter plots and regression models.

2.4. The Social Progress Index (SPI)

The Social Progress Index (SPI), conceived by Michael E. Porter and a team of economists, has emerged as a complementary measure to Gross Domestic Product (GDP), introduced in 2013 to assess social well-being in a more holistic way. The SPI transcends mere economic analysis, incorporating social and environmental aspects that are essential for a more comprehensive view of human development. This index is divided into three main areas – Basic Human Needs, Foundations of Well-being and Opportunities – and twelve varied components (Figure 3) ranging from Nutrition and Basic Medical Care to Access to Higher Education (Porter et al., 2013).

Applying the SPI to specific municipalities allows for a multidimensional assessment of development which, in addition to access to goods and services, considers the importance of people's living conditions (Stiglitz et al., 2009).

The prevailing model of economic development has failed to address these critical issues, making it imperative to seek new ways of understanding and measuring development. The SPI thus offers an alternative route, prioritizing socio-environmental aspects and providing a set of valuable information that is often neglected in traditional economic analyses.

This research used the most recent version of the SPI (updated in 2021) to explore the relationship between land use planning and socio-environmental indicators, as a means of assessing social progress in the municipalities of Tocantins state. The SPI Amazon has been published since 2014 under the leadership of IMAZON on a sub-national scale (states and municipalities), and this method has been adapted for other countries in the European Union, Central America, Asia, and Africa, as well as the United States (Santos et al., 2021).

Figure 3. Structure of the Social Progress Index at the component level.
Source: SPI Amazon, 2022.

3. Results

3.1. Social Progress Index in Tocantins

The relative distribution of SPI scores in the 139 municipalities of Tocantins, analyzed in 10 (ten) frequencies, can be seen in Figure 4. This distribution can be grouped into three categories: the first group of municipalities, which represents 33% of the total, is below the average of 54.08 points; 37% is in the average range and the third group, made up of 29% of the municipalities, is above average.

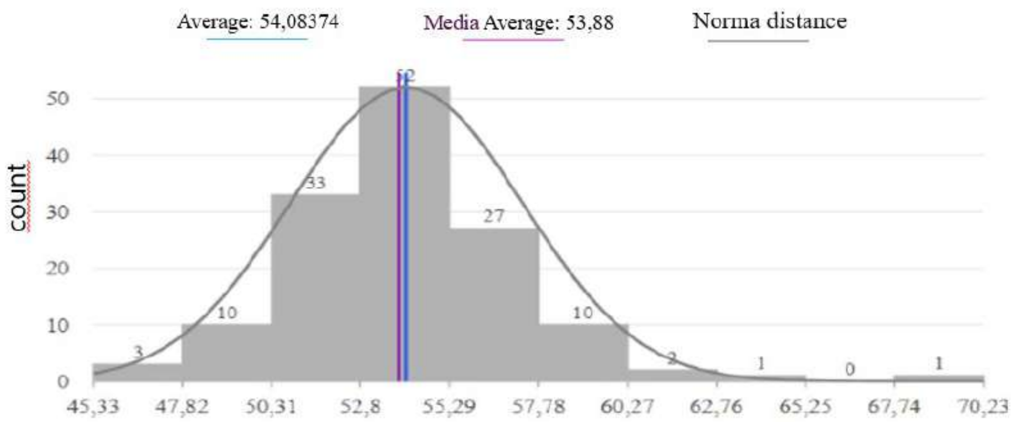


Figure 4. Distribution of SPI scores for the 139 municipalities of Tocantins.

The lowest scores were observed in three municipalities: Recursolândia, Goiatins and Porto Alegre de Tocantins, with scores of 45.33. Next were Conceição do Tocantins with 47.97 and Lagoa do Tocantins with 49.14. These are the five worst-performing municipalities in the state.

On the other hand, the highest score recorded was 70.23 for the municipality of Palmas, the state capital. Next was Fátima with 63.3, Porto Nacional with 61.44, Tupiratins with 60.37 and Figueirópolis with 59.83. These are the five municipalities with the best performance in the state. Therefore, these 10 municipalities were chosen as objects of analysis for the purposes of comparing land use planning and SPI.

Figure 5 shows the spatial distribution of these ten municipalities. The three municipalities with the highest scores in the SPI Amazon, Palmas, Porto Nacional and Fátima, are in contiguous positions, so Palmas is an immediate neighbor of Porto Nacional and Porto Nacional is an immediate neighbor of Fátima, thus forming a spatial connectivity between these three geographical units.

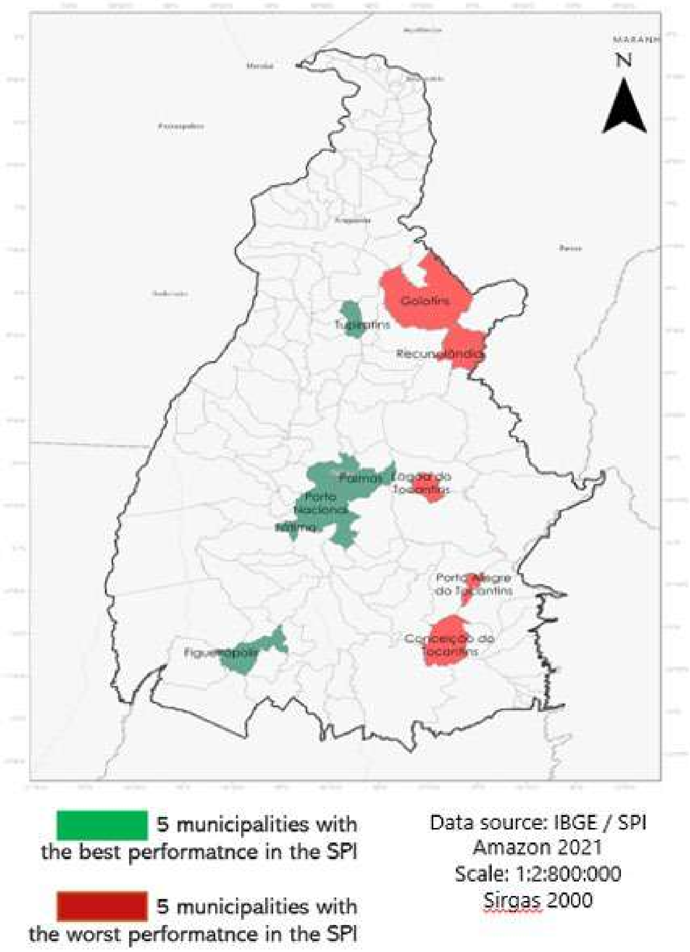


Figure 5. The five municipalities with the five best and the five worst performances in the SPI in Tocantins.

3.2. Land Concentration

The fiscal module is a concept introduced in 1979 by Law No. 6,746 (1979), which regulates the rights and obligations relating to rural properties, for the purposes of implementing agrarian reform and promoting national agricultural policy. It is a unit of area (expressed in hectares) set differently for each municipality, as it takes into account local particularities.

In relation to size, rural properties are classified as: Small Property, with an area of up to 4 fiscal modules; Medium Property, with an area of more than 4 and up to 15 fiscal modules; Large Property, with an area of more than 15 fiscal modules. The classification is defined by Law No. 8,629 (1993), amended by Law No. 13,465 (2017), and takes into account the fiscal module, which varies from 5 to 110 hectares according to the characteristics of the region. In the state of Tocantins, in the Legal Amazon, the fiscal module varies from 70 to 80 hectares.

The relationship between SPI and land concentration was determined by classifying rural properties into three size classes, based on fiscal modules considered in Tocantins. The classes were defined as: (i) Small, up to 320 hectares; (ii) Medium, from 320 hectares to 1,200 hectares; (iii) Large, more than 1,200 hectares.

There was a significant relationship between SPI and land concentration ($p > 0.05$). Deviance analysis and Chi-squared (both $p < 0.05$) confirm a significant effect between property size and SPI. This rejects the null hypothesis that the SPI is the same for all municipalities, regardless of the number of small rural properties. There was a positive correlation between an increase in SPI and the number of small rural properties, as shown in Figure 6. In Figure 6 we can see that the confidence intervals include values within the expected range for the true value of the parameter estimated by the model (95%). The intercept represents the average SPI value for municipalities with zero small rural properties (52.5; 95% CI: 51.7–53.3). The slope represents the variation in the SPI for each additional unit of small rural properties (0.002; 95% CI: 0.001–0.004).

However, for medium-sized areas, the correlation was not significant. According to the model, there is no association between GSP and the total number of medium Properties ($p = 0.48$). On the other hand, there is statistically significant evidence to reject the null hypothesis that the SPI is the same for all municipalities ($p < 0.05$), regardless of the number of large rural properties. We observed that the SPI decreases as the number of large rural properties increases (Figure 7).

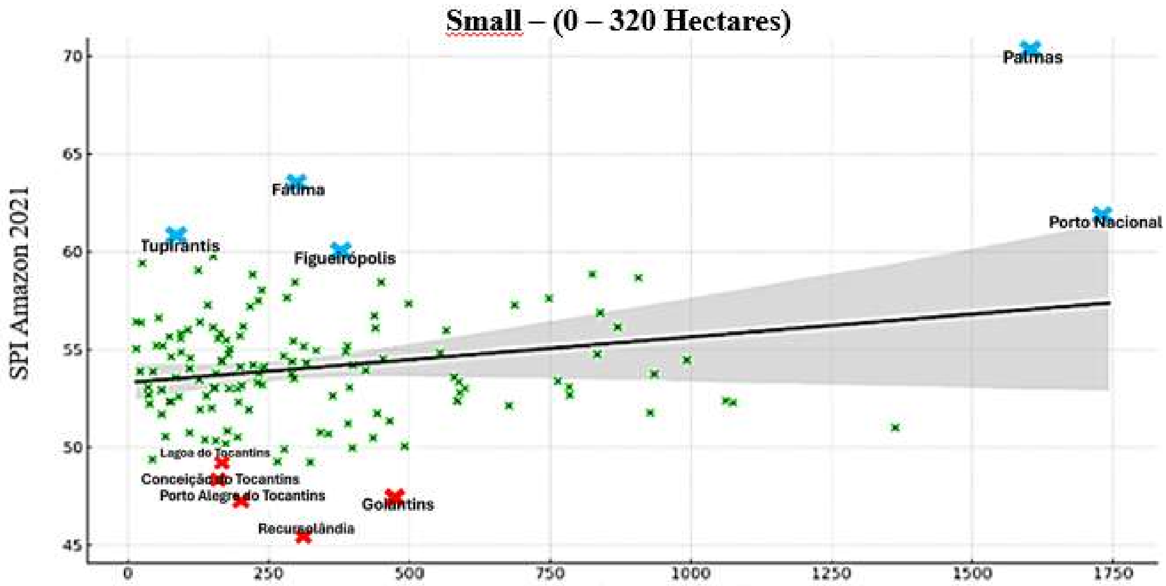


Figure 6. Linear regression between SPI and land concentration for small rural properties.

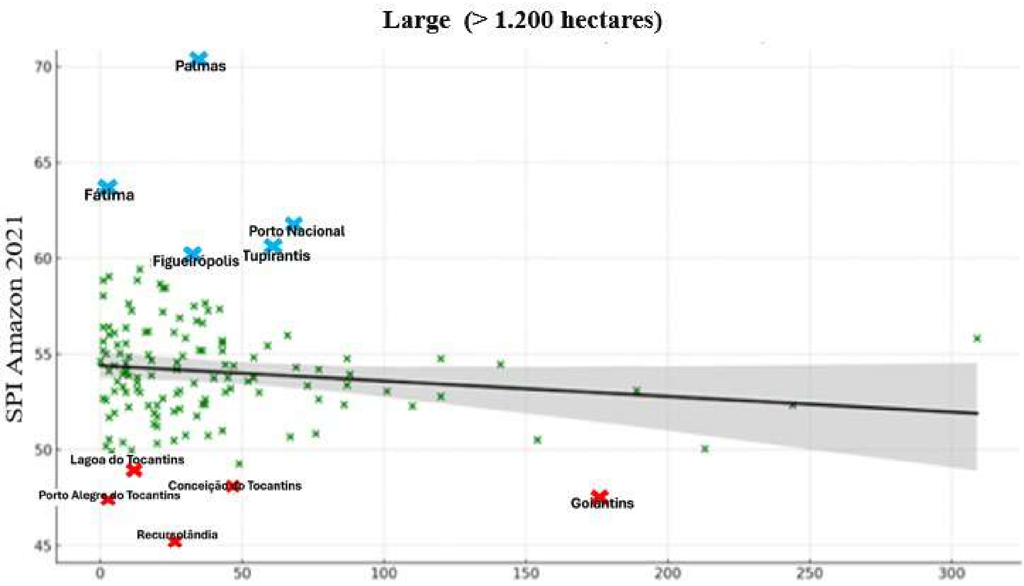


Figure 7. Linear regression between SPI and land concentration for large rural properties (> 1,200 hectares).

The confidence intervals are within the expected range for the true value of the estimated parameter (95%). The intercept represents the average GSP value for municipalities with zero large rural properties, 54.4 (54.5; 95% CI: 53.6–55.2), where the slope represents the variation in the SPI for each additional unit of large rural properties (−0.011; 95% CI: −0.019–0.004).

The correlation between the legal security of properties and the SPI score, based on the classification of legal security in terms of property status ($R^2 = 0.67$, $p < 0.005$), shows that there is a significant relationship between the number of properties and the SPI in the municipalities analyzed. The relationship between land possession and SPI was lower ($R^2 = 0.52$, $p = 0.020$). The equations, the correlation coefficient, and p-values of each regression are disposed in Table 2.

Table 2. Regression coefficient, equation, and p-values of multiple linear regressions between SPI, land concentration (small, large), legal security, and land tenure in the state of Tocantins, Brazil.

Relationship	R^2	Equation	p
SPI X land concentration for small rural properties	0.67	SPI = 52.5 + 0.002 × Number of Small Properties	< 0.005
SPI X land concentration for large rural properties	0.67	SPI = 54.5 − 0.011 × Number of Large Properties	< 0.005
SPI X legal security of properties	0.67	SPI = 53.506 + 0.001217 × Total Properties	< 0.005
SPI X land tenure	0.52	SPI = 53.506 + 0.00001207 × Total Land Tenure	< 0.05

4. Discussion

Land concentration has been central to the rural development debate, highlighting how the unequal distribution of resources impacts power, inequalities and sustainability (Robbins, 2020). Land concentration reflects the historical marginalization of indigenous populations and traditional communities, limiting their access to land and undermining their autonomy. From the perspective of environmental justice, it is observed that agricultural expansion in the Amazon accentuates imbalances by displacing indigenous peoples and overloading ecosystems (Sundberg, 2014).

Indeed, studies show that undemarcated indigenous territories are the most threatened by deforestation. Data from the Socio-Environmental Institute (Soares, 2025) indicate that only 5.89% of the original vegetation of official Indigenous Lands has been deforested, while the area outside Indigenous Lands has lost 54.4% of its vegetation.

Comparatively, in Latin America, countries such as Argentina and Paraguay present similar dynamics of land concentration, with adverse socio-environmental effects, especially for small farmers and indigenous peoples (Borras & Franco, 2013). Globally, Sub-Saharan Africa and Southeast Asia face similar challenges, with the expansion of monocultures for export often resulting in environmental degradation and loss of livelihoods (Hall et al., 2015).

Theoretical perspectives and global studies demonstrate that land concentration is not just a local issue but reflects trends of exclusion and injustice that cross borders, requiring policies that can promote equitable redistribution and socio-environmental resilience.

This study generated relevant information on the land structure and socio-environmental development of the municipalities in Tocantins state, as measured by the Social Progress Index (SPI). The inverse correlation identified between the concentration of land in large properties and the SPI highlights a worrying scenario: the accumulation of resources and power in a few hands seems to compromise the social well-being of the municipalities analyzed. This finding echoes the concerns raised by Sachs (2015) and Sen (1999), who argue that a more equitable distribution of resources is crucial to promoting social and environmental well-being.

On the other hand, municipalities with a more balanced land structure, especially those with a significant number of smaller properties, showed a higher SPI. This finding underscores the importance of public policies aimed at fairer land distribution, a view supported by Borras and Franco (2013), who highlighted the need for policy approaches that counter land concentration and promote social justice.

An important finding was the association between the legal security of land and the SPI score. The model suggests that municipalities with a greater number of properties tend to have a higher SPI, which was not observed in the case of land possession. This strengthens the idea that land regularization can lead to improvements in the socio-environmental indicators of municipalities.

This study broadens the understanding of the complex interaction between land structure and socio-environmental development, paving the way for future research. However, the research also identified challenges in land governance in Brazil, marked by the fragmentation of land registers and a lack of communication between the various bodies responsible for these records. This issue was highlighted by Guedes and Reydon (2012), who emphasize the need for an integrated land registration system to promote transparency and legal security in the country. Additionally, Viana

(2021) stresses the necessity of a systemic approach to sustainable territorial development, highlighting that a holistic and integrated vision is essential to address the complex problems that arise in territories with specific socio-environmental characteristics.

The association between legal land security and SPI suggests that effective land regularization policies can play a fundamental role in improving the socio-environmental indicators of municipalities, a view supported by Barbosa et al. (2006), who defend the importance of land regularization for sustainable development.

The search for comparative methods, considering indicators that are already consolidated and have a socio-environmental context, as in the case of the SPI, in parallel with the construction of methods for a broader understanding of the municipal land structure, could be a way of supporting public policies aimed at rural development.

5. Conclusions

This study sought to shed light on the complex relationships between land-use planning and socio-environmental development, using the Social Progress Index (SPI) as a reference. The implications of land concentration emerged as the most provocative findings of the research.

The results shown here indicate a significant association between the size of rural properties and the SPI in the municipalities analyzed. Municipalities with a higher concentration of land in large properties tend to have a lower SPI. At the same time, the data suggests that a more equitable distribution of land, particularly in municipalities where properties are smaller, is associated with better socio-environmental indicators. This is a crucial finding because it challenges traditional land policies under an economic development model that often neglects not only land reform in the country but also the equitable distribution of natural resources. The results obtained not only reinforce the central hypothesis of the research but also serve as an argument for the revision and reformulation of land policies towards more inclusive and sustainable development.

Although the data show a strong tendency for a relationship between the variables, the mechanisms that explain the nature of this relationship in more detail were not explored. Future research, some of which is already underway, should seek to expand the sample to other regions of the Legal Amazon to confirm the trends found for the state of Tocantins. An in-depth study of a set of cases, microregions, or municipalities, is also necessary to identify the mechanisms that lead land concentration to influence local social indicators.

CRediT Author Statement: Raimundo Fagner Frota Vasconcelos: Conceptualization, Methodology, Data curation, Investigation, and Writing-original draft; **Mário Lúcio Ávila:** Conceptualization, Methodology, Data curation, and Supervision; **Marcelo Ximenes Aguiar Bizerril:** Investigation, Supervision, Writing-original draft, and Writing-review & editing; **Tamiel Khan Baiocchi Jacobson:** Methodology, Investigation, and Writing-review & editing; **Marcelo Mateus Trevisan:** Conceptualization and Data curation.

Data Availability Statement: Not applicable.

Funding: This research was partially financed within the scope of the cooperation between National Institute for Colonization and Agrarian Reform (INCRA) and University of Brasilia (UnB), in the Mais Amazônia project, process number 23106.105820/2020-66.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgments: Not applicable.

References

Barbosa, M., Fontes, M. L. P., Mencio, M., & Saule Júnior, N. (2006). *Manual de Regularização Fundiária em Terras da União* [Manual for land regularization on federal lands]. Secretary of the Patrimony of the Union Brazil. https://www.sema.ce.gov.br/wp-content/uploads/sites/36/2019/06/Manual-de-Regulariza%C3%A7%C3%A3o-Fundi%C3%A1ria-em-Terras-da-Uni%C3%A3o-Projeto-Orla-1.pdf

Borras, S. M., Jr., & Franco, J. C. (2013). Global land grabbing and political reactions 'from below.' *Third World Quarterly*, *34*(9), 1723–1747. https://doi.org/10.1080/01436597.2013.843845

Comissão Pastoral da Terra. (2022). *Conflitos no Campo Brasil 2022*. https://www.cptnacional.org.br/downlods?task=download.send&id=14302&catid=41&m=0

Dolci, P. C., Bergamaschi, E. A., & Vargas, L. M. (2008, October 22–24). Um mapa conceitual sobre pensamento sistêmico: Seus conceitos e autores [A concept map on systems thinking: Its concepts and authors]. Anais do Simpósio sobre Gestão e Inovação Tecnológica, Brasília, DF, Brazil. https://pt.scribd.com/document/411388174/Um-Mapa-Conceitual-Sobre-Pensamento-Sistemico

Favareto, A., Nakagawa, L., Pó, M., Seifer, P., & Kleeb, S. (2019). *Entre chapadas e baixões do Matopiba: Dinâmicas territoriais e impactos socioeconômicos na fronteira da expansão agropecuária no cerrado* [Between the plateaus and lowlands of Matopiba: territorial dynamics and socio-economic impacts on the frontier of agricultural expansion in the cerrado]. Ilustre Editora. https://cebrapsustentabilidade.org/assets/files/entre_chapadas_e_baixoes_do_motopiba.pdf

Food and Agriculture Organization of The United Nations. (2012). *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security*. https://doi.org/10.4060/i2801e
Food and Agriculture Organization of The United Nations & Secretaria Especial de Agricultura Familiar e do Desenvolvimento Agrário (SEAD). (2017). *Governança de terras: Da teoria à realidade Brasileira* [Land governance: From theory to Brazilian reality]. https://www.economia.unicamp.br/images/publicacoes/Livros/geral/Governanca%20de%20Terras%20da%20Teoria%20a%20Realidade%20Brasileira.pdf#page=219
França, C. G. de, & Marques, V. P. M. (2017). O Brasil e a implementação das Diretrizes Voluntárias da Governança da Terra, da Pesca e dos Recursos Florestais: Aspectos da experiência recente [The Brazil and the implementation of the Voluntary Guidelines on the Governance of Land, Fisheries, and Forests: aspects of recent experience]. In R. S. Maluf & G. Flexor (Eds.), Questões agrárias, agrícolas e rurais: Conjunturas e políticas públicas (pp. 82–95). https://governancadeterras.com.br/wp-content/uploads/2017/10/Fran%C3%83%C2%A7a-2.pdf
Furtado, C. (2007). *Formação econômica do Brasil* [Brazil's economic formation]. Companhia Editora Nacional.
Guedes, S. N. R., & Reydon, B. P. (2012). Direitos de propriedade da terra rural no Brasil: Uma proposta institucionalista para ampliar a governança fundiária [Rural land property rights in Brazil: An institutionalist proposal to expand land governance]. *Revista de Economia e Sociologia Rural*, *50*(3), 525–544. https://doi.org/10.1590/S0103-20032012000300008
Hall, R., Scoones, I., & Tsikata, D. (2015). Africa's land rush: Rural livelihoods and agrarian change. James Currey Ltd.
Harvey, D. (1973). *Social justice and the city*. Johns Hopkins University Press.
Holanda, S. B. (2007). *Raízes do Brasil* [Roots of Brazil]. Companhia Editora Nacional.
Law No. 6,746, of December 10, 1979. Regulates the rights and obligations relating to rural properties for the purposes of agrarian reform implementation and national agricultural policy promotion. (1979). https://www.planalto.gov.br/ccivil_03/leis/1970-1979/L6746.htm
Law No. 8,629, of February 25, 1993. Regulates agrarian reform and the expropriation of rural properties that do not fulfill the social function, taking into account the fiscal module in the classification of rural properties. (1993). https://www.planalto.gov.br/ccivil_03/LEIS/L8629.htm
Law No. 13,465, of July 11, 2017. Amends Law No. 8,629/93 with provisions related to land regularization, fiscal modules, and rural property classification. (2017). https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13465.htm
McCullagh, P., & Nelder, J. A. (1989). *Generalized Linear Models* (2nd ed.). Chapman and Hall.
Menezes, R. G., & Barbosa, R., Jr. (2021). Environmental governance under Bolsonaro: Dismantling institutions, curtailing participation, delegitimizing opposition. *Zeitschrift für Vergleichende Politikwissenschaft*, *15*, 229–247. https://doi.org/10.1007/s12286-021-00491-8
1988 Constitution of the Federative Republic of Brazil. Federal Senate, Brasília, DF. (1988). http://www.planalto.gov.br/ccivil_03/Constituicao/Constituicao.htm
Pereira, J. M. M., & Sauer, S. (2011). A "reforma agrária assistida pelo mercado" do Banco Mundial no Brasil: Dimensões políticas, implantação e resultados [The World Bank's "market-assisted land reform" in Brazil: Political dimensions, implementation and results]. *Sociedade E Estado*, 26(3), 587–612. https://doi.org/10.1590/S0102-69922011000300009
Porter, M. E., Stern, S., & Loría, R. A. (2013). *Social Progress Index 2013*. Social Progress Imperative. https://hazrevista.org/wp-content/uploads/social_progress_index_2013.pdf
Robbins, P. (2020). *Political ecology: A critical introduction* (4th ed.). Wiley-Blackwell.
Sachs, J. D. (2015). *The age of sustainable development*. Columbia University Press.
Sant'anna, A. A. (2017). Land inequality and deforestation in the Brazilian Amazon. *Environment and Development Economics*, *22*(1), 1–25. https://doi.org/10.1017/S1355770X1600022X
Santos, D., Veríssimo, A., Seifer, P., & Mosaner, M. (2021, December 6). *Índice de Progresso Social na Amazônia Brasileira – IPS Amazônia 2021* [Social Progress Index for the Brazilian Amazon - IPS Amazônia 2021]. Imazon and Amazônia 2030. https://imazon.org.br/publicacoes/ips-amazonia-2021/
Santos, M. (2006). *A natureza do espaço: Técnica e tempo, razão e emoção* [The nature of space: Technique and time, reason and emotion] (4th ed.). Editora da Universidade de São Paulo.
Santos, R. S. (2020). (Des)envolvimento regional, fronteira e o espaço do agronegócio no Tocantins: Crescimento econômico sem distribuição de renda [Regional disembeddiment, frontier and the space of agribusiness in Tocantins: Economic growth without income distribution]. *DRd - Desenvolvimento Regional em Debate*, *10*, 3–35. https://doi.org/10.24302/drd.v10i0.2509
Sauer, S., Leite, A. Z., & Tubino, N. L. G. (2020). Agenda política da terra no governo Bolsonaro [Politicial agenda for land by the Bolsonaro Government]. *Revista da ANPEGE*, *16*(29), 283–316. https://www.researchgate.net/publication/346273877
Sauer, S., & Pereira Leite, S. (2012). Agrarian structure, foreign investment in land, and land prices in Brazil. *The Journal of Peasant Studies*, *39*(3–4), 873–898. https://doi.org/10.1080/03066150.2012.686492
Sen, A. (1999). *Development as freedom*. Companhia das Letras.
Smith, N. (1984). *Uneven development: Nature, capital, and the production of space*. University of Georgia Press.
Soares, M. (2025, January 21). *Terras Indígenas na Amazônia e no Cerrado protegem uma área de vegetação nativa maior que o estado de Mato Grosso* [Indigenous Lands in the Amazon and Cerrado protect an area of native vegetation larger than the state of Mato Grosso]. Instituto Socioambiental. https://www.socioambiental.org/noticias-socioambientais/terras-indigenas-na-amazonia-e-no-cerrado-protegem-uma-area-de-vegetacao
Stiglitz, J. E., Sen, A., & Fitoussi, J. P. (2009). *The measurement of economic performance and social progress revisited*. français des conjonctures économiques (OFCE). https://www.ofce.sciences-po.fr/pdf/dtravail/WP2009-33.pdf?simple=True
Sundberg, J. (2014). Decolonizing posthumanist geographies. *Cultural Geographies*, *21*(1), 33–47. https://doi.org/10.1177/1474474013486067
Valença, M. (2010). O Território como Referência para o Desenvolvimento Rural: Concepções e Implicações Metodológicas para o Caso Brasileiro [The territory as a reference for rural development: Conceptions and methodological implications for the Brazilian case]. In M. I. M. Turazzi (Org.), *Desenvolvimento territorial no Brasil: Múltiplos olhares* (pp. 21–38). Mauad X.
Veiga, J. E. (2005). *Desenvolvimento sustentável – o desafio do século XXI* [Sustainable development: The challenge of the 21st century]. Editora Garamond.

Viana, V. (2021). Abordagem sistêmica para o desenvolvimento sustentável da Amazônia Profunda [Systemic approach to sustainable development of the in-deepth Amazon]. *Revista Tempo do Mundo*, 27, 1–24. https://repositorio.ipea.gov.br/bitstream/11058/13332/1/Tempo_Mundo_27_Artigo3_abordagem_sistemica.pdf
Wickham, H., & Grolemund, G. (2016). *R for data science: Import, tidy, transform, visualize, and model data*. O'Reilly Media Inc.
Williamson, I. P. (2001). Land administration "best practice" providing the infrastructure for land policy implementation. *Land Use Policy*, *18*(4), 297–307. https://doi.org/10.1016/S0264-8377(01)00021-7
Williamson, I. P., Enemark, S., Wallace, J., & Rajabifard, A. (2010). *Land administration for sustainable development*. ESRI Press Academic.
World Bank Group. (2014). *Brazil land governance assessment*. https://documents1.worldbank.org/curated/en/105561468191049199/pdf/89239-ENGLISH-ESW-PUBLIC-Portuguese-already-in-ImageBank-Box393197B.pdf

Agricultural & Rural Studies

Article

Communicating Cleaner Production Among Value-Chain Actors Through Actionable Guidelines for Climate-Smart Agriculture Implementation in South Africa: A Content Analysis

Oladimeji Idowu Oladele [1]

1 School of Agriculture, Environment and Earth Sciences, University of Kwa-Zulu Natal, Pietermaritzburg 3201, South Africa; Oladeleo@ukzn.ac.za

Abstract: In light of cleaner production methods and the framing and stylization of communication via the lens of agroecological principles, this study content examined practical recommendations for the implementation of climate-smart agriculture in South Africa. This study used content analysis, a conceptual analysis technique that identifies the presence and frequency of concepts in a text. Social values, co-creation of knowledge, and inputs are practices with the highest frequency on response, while synergy, fairness, governance, animal health, and recycling are vulnerable cleaner production practices follow the frequency of codes in decreasing order. In contrast to efficacy-induced communications on cleaner production methods, which were coded 54 times, threat-induced messages on cleaner production were coded 28 times. The actionable instructions on climate-smart agriculture coded the present incidence of cleaner production techniques 44 times and the future incidence 65 times. Practice action was tagged 76 times and non-practice action was coded 25 times in the actionable guidelines on climate-smart agriculture, which outlined practical measures to be followed for the adoption of cleaner production. The findings have implications for future and existing incidence, practice actuation and non-practice actuation, and treatment-induced and efficacy-induced communication connected to cleaner manufacturing practices.

Keywords: cleaner production; climate smart-agriculture; communication framing; climate messages

Citation: Oladele, O. I. (2025). Communicating Cleaner Production Among Value-Chain Actors Through Actionable Guidelines for Climate-Smart Agriculture Implementation in South Africa: A Content Analysis. *Agricultural & Rural Studies*, *3*(1), 11. https://doi.org/10.59978/ar03010006

Received: 29 March 2024
Revised: 1 July 2024
Accepted: 21 January 2025
Published: 10 March 2025

1. Introduction

Cleaner production has been defined in a variety of ways as a collection of environmental practices used to minimize waste, prevent pollution, change products, handle chemicals safely, and reduce operating, waste, and raw material costs. It also reduces pollution of the air and water, ozone depletion, global warming, and resource depletion. "The continuous application of a preventive and integrated environmental strategy applied to processes, products, and services in order to increase efficiency and reduce risks to humans and the environment" is how the United Nations Environment Programme (UNEP) defined cleaner production (Shi et al 2021). Shin et al. (2008) state that cleaner production is a "strategic approach that transforms unsustainable development into environmentally friendly that can balance the socioeconomic and environmental needs of countries."

Globally, about half of all emissions generated by food systems occur at the farm level, emanating from synthetic fertilizers use and the reduction of organic soil matter; exploring the need for nature-based solutions through regenerative agriculture and agroecology principles, such as recycling, greening, and soil carbon sequestration among others. In agriculture, cleaner production practices are methods that reduce the use of natural resources and waste generated during production, by using cleaner technologies, modifying operating parameters, and using greener materials. The prominent cleaner agricultural production measures cover major areas on reduction and substitution of fertilizer use, reduction and efficiency enhancement of pesticides, straw utilization, water-saving and solar-powered irrigation, and agricultural recycling. The cleaner production practices are hinged on the enhancement of biodiversity through agroforestry, use of species that support ecosystem services, crop rotation, intercropping, enhancement of intraspecific diversity, nutrient cycling, natural pest management, and polyculture, diversifying animal population.

The global pursuit of sustainable development has highlighted the need for cleaner production practices in which agricultural extension services have been providing different models and strategies for communication with practitioners along the value chain. The agricultural extension can be defined as the entire set of organizations that support people engaged in agricultural production and facilitate their efforts to solve problems, link to markets and other players in the agricultural value chain, and obtain information, skills, and technologies to improve their livelihoods (Davis et al., 2020). According to Yanfika et al. (2024), Agricultural extension services are channels for knowledge dissemination, training provision, and innovation facilitation in the agricultural sector, bridging the gap between research, policy, and implementation, enhancing farmers transitioning to cleaner production practices. Branca and Perelli (2020) noted that the diffusion and adoption of climate-smart technologies are critical for African smallholder farmers to achieve a sustainable transition towards cleaner, circular, and more productive food systems. Saifan et al. (2021) found that extension services and climate change are vital factors that can affect the farm level outcomes like income and output and that increased access to education and experience of farmers were related to the extension services received by the farmers.

Wulandari (2022) reported that the strategies for improving cleaner production practices include developing knowledge transfer, enhancing farmer skills, and processing infrastructure and technology provision through extension services. Mburu et al. (2024) reported that it is imperative to strengthen the pluralistic extension system, increase extension contacts with farmers, and train farmers on climate change for intensified promotion and intensified uptake of the least adopted dairy climate-smart practices. According to Hilmi et al. (2024), farmers' knowledge, skills, comprehension, training, and extension services are crucial for climate change adaptation and mitigation tactics. According to Kalogiannidis and Syndoukas (2024), agricultural extension services enhance farmers' organizations and last-mile agricultural input providers, bridge the knowledge gap between research and actual farming, and facilitate access to better inputs, appropriate production methods, and knowledge. This is necessary to boost farm productivity and sustainability on a large scale.

Cleaner production methods are part of Climate Smart Agriculture (CSA), and as a result, the practical recommendations for CSA practice implementation in South Africa list many methods to facilitate the shift to a green economy that benefits everybody. A number of agroecological concepts were also mentioned as workable methods for agriculture to accomplish adaptation and mitigation goals (England et al., 2018; High Level Panel of Experts on Food Security and Nutrition [HLPE], 2019). The specifics of the unusual communication patterns have an impact on South Africa's acceptance and execution of climate change policies, according to Poortvliet et al. (2020).

Communicating Climate Change and Cleaner Production

Communicating climate change is about educating and mobilizing audiences to take action to confront the climate crisis as shaped by different experiences, cultural contexts, and underlying values. Donlon (2023) reported that "mis- and disinformation are widespread on the issue of climate change and across digital platforms, as bad-faithed actors are sowing doubt and confusion, with the aim of delaying or obstructing action on the climate crisis." The Intergovernmental Panel on Climate Change (IPCC, 2021) reported that "rhetoric and misinformation on climate change and the deliberate undermining of science have contributed to misperceptions of the scientific consensus, uncertainty, disregarded risk and urgency, and dissent." Doyle (2022) noted that communication on climate change should enhance more diverse narratives that go beyond catastrophic imageries but more clearly center on climate justice within popular cultural complexities. Yusuf and St John (2021) noted that communicating climate change explores access, relevance, and understandability as key elements to provide an overview of how these aspects allow multiple groups of stakeholders to act on climate-related information to build resilience. Lee et al. (2024) stated that utilizing systems approaches to understand and anticipate how information may be distributed and received can lead to more proactive climate communication.

According to Evans et al. (2018), there are a number of different paradigms from which climate change communication has been theorized. These paradigms include risk communication, development journalism, environmental communication, advocacy journalism, and communication for social change and development. Conflicting values and social dilemmas result from the misalignment of values between the climate message and its audience, according to Boakye et al. (2023). This is why climate change messages are rejected and psychological denial is caused by a lack of goal specifications, fear, blaming, and negative criticism. According to Sippel et al. (2022), people determine their opinions about climate communication by evaluating expert knowledge, looking at cost-benefit analysis, and evaluating the relationships between emotions and values.

According to Maibach et al. (2023), society's response to climate change is improved by evidence-based heuristic attempts to disseminate science-based knowledge about the phenomenon. Communication tactics that focus climate messages on iconic locations may encourage action, and communications that highlight collective efficacy can increase message effects and impact the adoption of a wider variety of behaviors, according to Waters et al. (2024). In the analysis of the ways in which climate scientists, climate doubters, and climate activists communicate their (un)certainty, Penz (2022) came to the conclusion that communication alone cannot account for the failure to advance climate action. According to Peters et al. (2022), ideas and practices for communicating about climate change should be grounded in theory and backed by data.

The Extended Parallel Process Model (EPPM), which explains how people react to frightening messages and is based on perceived danger, self-efficacy, response efficacy, and response, is one of the communication theories examined in this study. Individuals must feel threatened by the consequences of specific behavior, feel capable of taking the necessary action to avoid that threat, and believe that the action will be effective in preventing the incidence of the perceived threat in order to take protective action, according to the EPPM's climate messaging. The Constructal Level Theory (CLT) explains the connection between the widely recognized definitions of events and objects and the degree to which people's thoughts are categorized about them. When an object is closer to a person, it is perceived more concretely, and when it is farther away, it is thought of more abstractly. A concrete conceptual level may make climate change seem more psychologically approachable, which could lead to a greater acceptance of the issue and a greater willingness to address it, while an abstract conceptual level may make climate change seem more psychologically distant, which could lead to a lower acceptance of the issue and a decreased willingness to address it, according to Wang et al. (2019).

In addition, the use of risk communication in climate change has focused on the idea of a deficit model; in order to rectify factual errors, additional information is needed for comprehension and behavior modification. Perceptions of climate change risks and the ability to take action against those risks are crucial for encouraging adaptation and mitigation behaviors, according to a number of authors (Poortvliet et al., 2020; Branca & Perelli, 2020; Mujeyi et al., 2021). However, the content of communications and the existence, meanings, and connections of specific words, themes, and concepts could encourage the use of cleaner production methods.

How is communication about cleaner manufacturing framed? This is one of the research topics that emerges from this study. Which forms of communication are linked to more environmentally friendly production? Which aspects of communication are relevant to cleaner production methods? This paper's primary goal is to analyze the substance of the reports on climate-smart agriculture in South Africa, namely the cleaner production principles that were covered and the way that cleaner production communication was presented.

2. Materials and Methods

In order to investigate the existence, definitions, and connections of terms, themes, and concepts related to cleaner production methods, this article content-analyzed the practical recommendations for climate-smart agriculture implemented in South Africa. In order to ascertain whether or not concepts are included in a text, this study used the conceptual content analysis technique. Both overtly and covertly, the actionable guidelines' use of cleaner production, agroecology concepts, and communication framing were analyzed. Dictionary or contextual translation rules, or both, were used to code the explicit and implicit terms. The results were then analyzed by making generalizations and deductions.

This analysis approach is based on the observation that, in spite of the substantial amount of CSA knowledge that is available in South Africa, there aren't many useful recommendations for putting cleaner production methods into reality. According to Mnkeni et al. (2019), CSA approaches have been established as stand-ins for cleaner production practices. The actionable guidelines are based on the goals of guiding actions at all levels on improving resilience to climatic shocks, helping to reduce national emission intensity, and ensuring that climate-smart agriculture is implemented effectively at all levels.

Only two volumes of actionable guidelines were examined in this study: "Actionable Guidelines for the Implementation of Climate-Smart Agriculture in South Africa." Volume 1, titled "Situation Analysis and Useful Advice for South Africa's Climate-Smart Agriculture Implementation," contains 106 pages with 46,091 words. Volume 2, titled "Climate Smart Agriculture Practices," consists of 201 pages with 98,721 words. The country's move to cleaner production is made possible by the two volumes' comprehensive explanations of the advantages of adopting techniques identified and illustrated as CSA by value chain operators. The two books included sections on managing soil and water, cropping systems based on cereals, sugar cane production, fruit production and viticulture, climatic information services, weather insurance based on the index, urban agriculture, management of pasturelands and rangelands, agroprocessing, marketing, sharing of information, social inclusion and gender, and policy concerns. The two volumes underwent content analysis by employing the concepts from cleaner production processes to code the reports' text. This allowed for the execution of distinct content analysis for each of the concepts. In accordance with the HLPE principles of agroecology, the following codes were used in the content analysis: recycling, inputs, soil health, animal health, biodiversity, synergy, economic diversification, knowledge co-creation, social values, fairness, connectivity, land and natural resources governance, and participation. Codes were applied to sentences or text passages that were determined to address an idea from one of the cleaning procedures.

As a result, each of the cleaner production concepts was used separately as a code, and the frequency of occurrences of each code was counted to determine the total frequency for each concept. This made the analysis quantitative and deductive (Hennink et al., 2019), and it concentrated on the frequency and timing of concepts in the report. The codes are used to determine the meanings and connections between specific phrases, topics, and concepts throughout the two volumes' many parts pertaining to cleaner production.

In order to consider the communication theories and models used in the actionable recommendations on climate-smart agriculture in South Africa, the study also conducted a content analysis of the guidelines using the extended parallel model, construal level theory, and deficiency model. To investigate the communication theories' dimensions on the deficit model, Constructal Level Theory (CLT), and Extended Parallel Process Model (EPPM), a general coding was used that cut across the risk communication theories as susceptibility, which includes fear and threat, and response, which covers the efficacy dimensions. The purpose of this general coding was to ascertain how well the practical recommendations for implementing climate-smart agriculture in South Africa used and articulated notions of susceptibility and responsiveness in connection to cleaner output. CLT stood for current incidence and future incidence, EPPM for threat-induced and efficacy-induced, and deficit model for practice-actuation and non-practice actuation. The codes' frequency counts and percentages were displayed using graphs.

3. Results

The findings include definitions of each code, as well as the frequency and percentages of cleaner practices coded in the examination of the coverage of actionable guidelines on climate-smart agriculture in South Africa. In the actionable guidelines on climate-smart agriculture reporting in South Africa, this article examined what cleaner production principles are included and how they have been used for communication. The underlying agroecological principles and theoretical frameworks of the extended parallel process model (EPPM), constructal level theory (CLT), and deficit model serve as the basis for this. These frameworks were coded as practice actuation and non-practice actuation, threat-induced and efficacy-induced, current incidence and future incidence, and so on.

The results and discussion part are divided into three sections: concepts related to risk communication theories, cleaner production practices, and indications of the extended parallel model, deficit model, and constructive level theory in practical guidelines. In the actionable guidelines on climate-smart agriculture, Figure 1 shows how often cleaner production strategies are used.

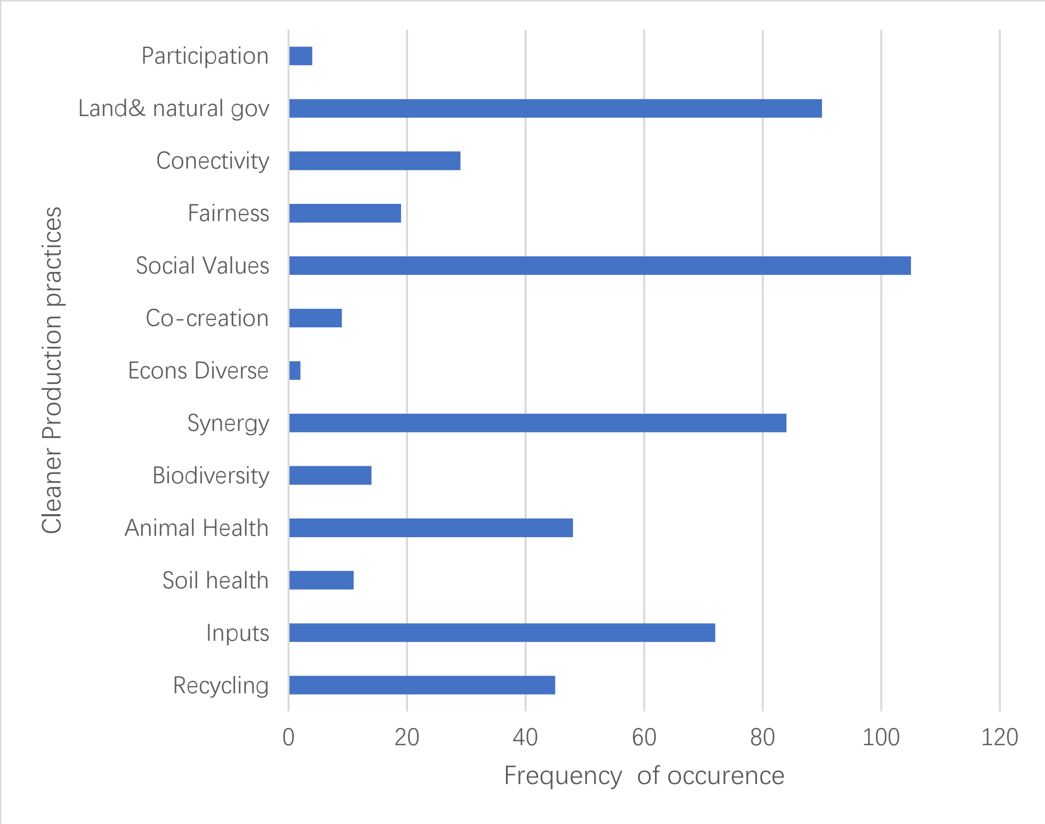


Figure 1. Frequencies of cleaner production practices.

4. Discussions

4.1. Figure 1 Results: Cleaner Production Practice Frequencies

As detailed in the following sections, the findings from Figure 1 addressed the cleaner production techniques that are communicated through actionable instructions on climate-smart agriculture.

4.1.1. Reusing and Recycling

The preferential use of local renewable resources and the closest possible resource cycles of biomass and nutrients are how HLPE (2019) operationalizes this. One of the most important cleaner production concepts identified in the text analysis of actionable guidelines on climate-smart agriculture is recycling. Recycling, which includes closed-loop, on-site, re-use, off-site, and reclamation including composting, animal manure, wastewater, grey water, and food wastes, saves money on waste handling, insurance premiums, and environmental damage costs.

4.1.2. Input Reduction

In order to assure cleaner production, the process of decreasing and removing reliance on purchased inputs and increasing self-sufficiency makes sure that inputs are processed, recycled, and reused while outputs reduce waste and emissions (Fet et al., 2023). As a cleaner production method, eco-efficiency in agriculture tackles all green, circular, and bioeconomy processes because agriculture produces a large amount of biomass (Tsangas et al., 2020; Jimenez-Lopez et al., 2020).

4.1.3. Soil Health

HLPE (2019) states that the actionable guidelines on climate-smart agriculture include zero and minimum tillage, integrated soil fertility management, conservation agriculture, compost, and biofertilizers. These practices are all part of the security and improvement of soil health and functioning for improved plant growth, especially by managing organic matter and enhancing soil biological activity. Similarly, vermicompost's humic compounds and improved microbiology activities reduce harmful environmental repercussions, ensuring a cleaner and greener process that involves bio-oxidation and stabilization (Bhattacharyya et al., 2021; Gupta et al., 2021).

4.1.4. Animal Health

As stated in the actionable guidelines on climate-smart agriculture, animal health is operationalized by HLPE (2019) as guaranteeing animal health and welfare through practices like crop-livestock integration, reduced enteric fermentation, recoupling of nutrient cycles, rangeland management, nutrition, welfare, and Holistic Regenerative Land Management (HLMR).

4.1.5. Biodiversity

At the field, farm, and landscape sizes, this is shown as the process of preserving and improving species variety, functional diversity, and genetic resources for the total biodiversity of agroecosystems over time and place (HLPE, 2019). According to Dawson et al. (2020) and the World Wide Fund for Nature (2021), species diversity increases productivity by providing essential ecosystem services, protects against the effects of drought and high temperatures, increases resilience to drought, floods, and other calamities, and lowers exposure to harmful synthetic agrochemicals.

4.1.6. Synergy

Synergy improves beneficial ecological interaction, synergy, integration, and complementarity among the components of agroecosystems (crops, trees, soil, water, and animals), claims HLPE (2019). According to research on Land Equivalent Ratios (LER), mixing two or more components in a production system enhances output compared to monocultures through an integrated system of biotic and abiotic diversity and alignment in time and space. This is related to recycling, using co-existing microbiomes to improve nutrient uptake and resilience (Singh et al., 2020).

4.1.7. Economic Diversification

Increasing small-scale farmers' financial independence and providing them with options for value addition will help them diversify their on-farm revenue streams and meet consumer demand (HLPE, 2019). This includes integrating waste and by-products from one activity to another, crop diversification, sustainable farming methods, and non-farm activities that reduce the risk of losses and improve resilience to environmental changes, as well as non-farm income-generating activities (Kurdyś-Kujawska et al., 2021).

4.1.8. Co-creation of Knowledge

The improvement of co-creation and horizontal information sharing, including local and scientific innovation, particularly through farmer-to-farmer exchange, is what HLPE (2019) defines as this. FAO (2021) and Glassman et al. (2018) state that in order to achieve sustainable development, agroecology necessitates a thorough understanding of the environment, culture, and social relevance. Co-creation and co-production of knowledge make it easier to connect different kinds of knowledge, improve sustainable results, encourage multi-stakeholder viewpoints, and encourage value-chain actors to learn and grow together.

4.1.9. Social Values

In order to create food systems that offer wholesome, varied, seasonally, and culturally appropriate meals, social values and diets are founded on the culture, identity, tradition, social equality, and gender of local communities (HLPE, 2019). The practical recommendations for climate-smart agriculture illustrated the social virtues of climate-smart adaptation and the advantages of diversity, including the intake of culturally significant foods and dietary diversity. According to Santoso et al. (2021), farmers benefit from more nutritional diversity when there is agrobiodiversity.

4.1.10. Fairness

All participants in food systems, particularly small-scale food producers, should have respectable and stable livelihoods based on fair trade, fair employment, and fair handling of intellectual property rights, according to HLPE (2019). "Cleaner production practices should improve codes of conduct, accountability, risk assessment, collaboration, control of their agricultural production, decision-making process, resource use, and livelihoods," the recommendations stressed (Principles for Responsible Investment, 2020).

4.1.11. Connectivity

By encouraging equitable and efficient distribution networks and reintegrating food systems into local economies, producers and consumers can maintain closeness and trust (HLPE, 2019). This promotes a circular and solidarity economy, whereby production and consumption minimise waste and optimize sustainability by extending the lifespan of materials and goods. Reusing and repurposing, recycling, cutting waste, and regenerating natural systems are all ideas that connectivity examines (Villalba-Eguiluz et al., 2023).

4.1.12. Land and Natural Resource Governance

HLPE (2019) operationalizes this as bolstering institutional frameworks to enhance, such as acknowledging and assisting smallholders, family farmers, and peasant food producers as sustainable managers of genetic and natural resources and as responsible governing bodies. Focusing on the benefits and opportunities for development, connecting climate policy to poverty reduction goals, providing clean energy to communities, and encouraging the growth of new low-carbon industries, helps to maximize opportunities to strengthen climate governance. Leveraging buy-in and effective engagement across levels of governance, both horizontally and vertically, is crucial (Averchenkova et al., 2019).

4.1.13. Participation

In order to enhance decentralized governance and local adaptive management of agricultural and food systems, HLPE (2019) advocates for social organization and increased involvement in decision-making by food producers and consumers. This entails farmer-to-farmer communication, empowering procedures, and the development of research agendas in participatory research (Dong et al., 2023).

4.2 Findings from Figure 2: Climate Smart Agriculture Actionable Guidelines' Susceptibility and Response Concepts for Cleaner Production

In the actionable suggestions on climate smart agriculture, the findings in Figure 2—which addressed susceptibility and response ideas in relation to cleaner production—are discussed in the following sections. In order to evaluate how well the practical suggestions for implementing climate-smart agriculture in South Africa implemented and conveyed notions of susceptibility and response in relation to cleaner production, the general coding across the three communication theories is described in this part. The content analysis of actionable instructions on climate-smart agriculture shows that the sustainable cleaner production practices of recycling, animal health, governance, synergy, and fairness have the highest frequency of codes in decreasing order. On the other hand, processes that receive a lot of responses include inputs, co-creation of knowledge, and social values. Value chain members' inclination to embrace cleaner production methods and the communication style's potential response is highlighted in the presentation of the actionable instructions. According to Duan et al. (2022), perceptions may change as a result of other role players' activities, but mitigation behavioral intentions are increased when production outlooks are perceived to be cleaner. Managers' and politicians' understanding of the threat posed by climate change affects their adoption of carbon offset programs and carbon neutrality (Wang et al., 2023).

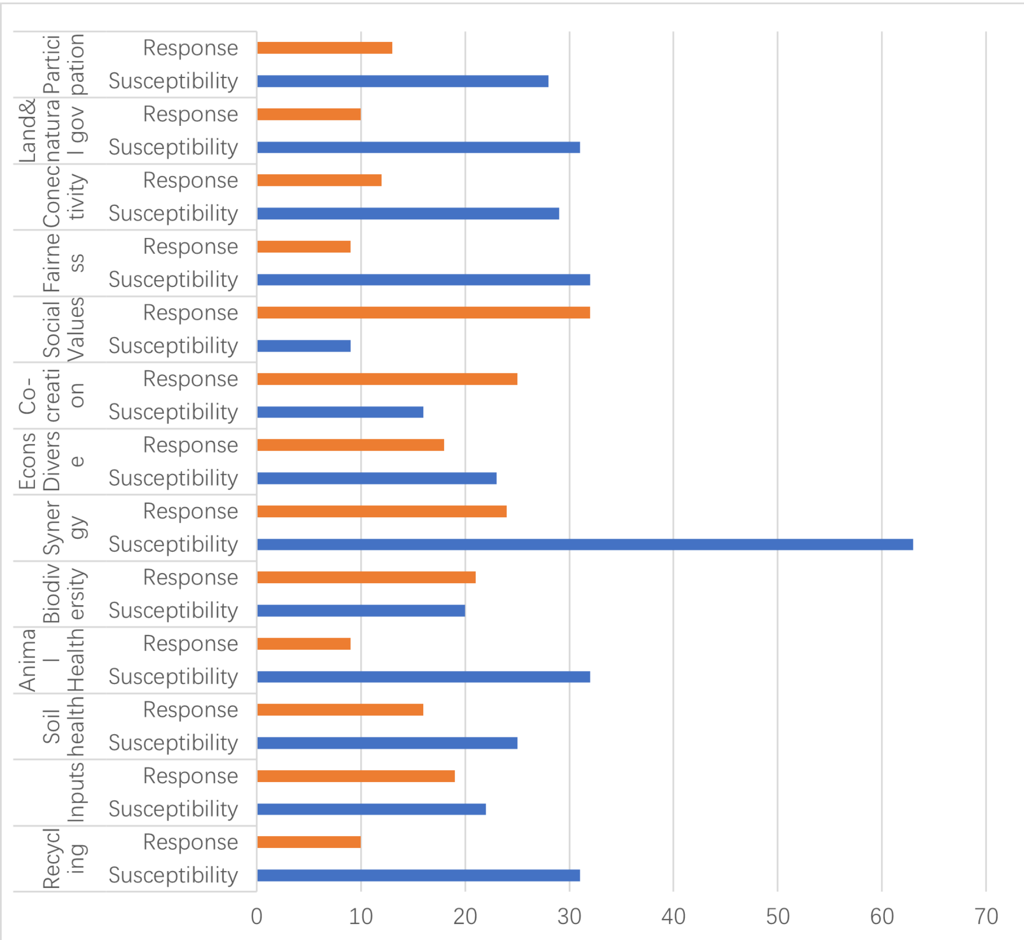


Figure 2. Frequency of concepts associated with risk communication theories in the actionable guidelines for climate smart agriculture.

4.3 Results from Figure 3: Indicators of the Deficit Model, Conceptual Level Theory, and Extended Parallel Model Frequencies in Practical Recommendations.

The indicators of the extended parallel model, construal level theory, and deficit model in relation to cleaner production practices in the actionable guidelines on climate-smart agriculture are presented in Figure 3 and are covered in the parts that follow.

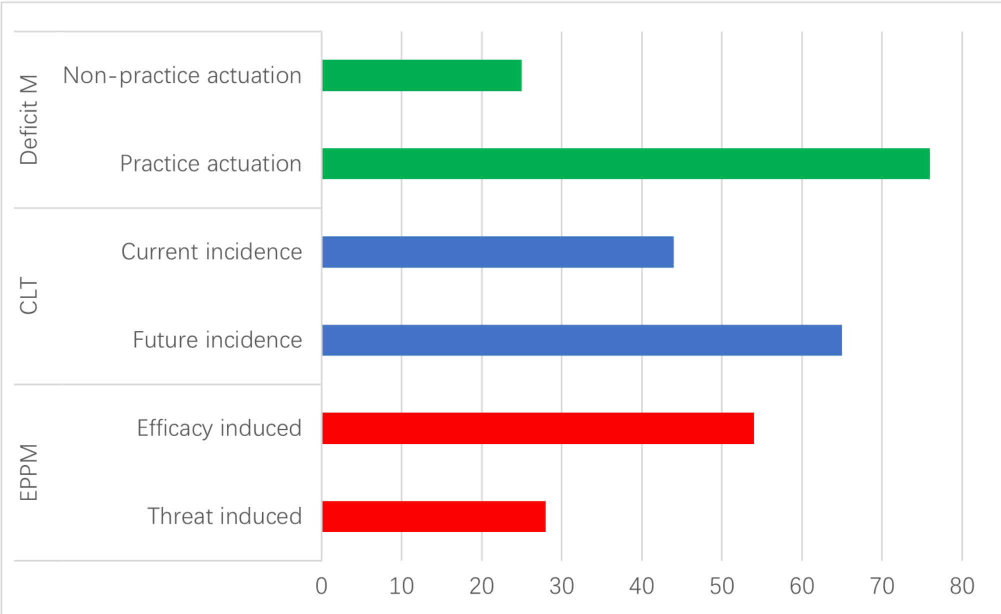


Figure 3. Frequencies of extended parallel model, construal level theory, and deficit model in actionable guidelines.

4.3.1. Threat-induced and Efficacy-induced

Threat-induced messages on cleaner production were coded 28 times, according to the content analysis of practical guidance on climate-smart agriculture. The recommendations created a threat by requiring clean production methods, which are necessary to prevent the spread of climate change's effects, including droughts, low productivity, and poor resilience. 54 different codes were used to encode efficiency-induced messages about cleaner production methods, which promoted recycling, reducing inputs, improving soil and animal health, and biodiversity, fostering collaboration, diversifying the economy, co-creating knowledge, social values, and fairness as ways to mitigate the effects of climate change. Improvements in soil structure, biomass conversion, soil carbon sequestration, and soil fertility would result from the effective response brought about by cleaner production methods. Environmental concerns and the impression of climate change encourage pro-environmental behavior (Chen et al., 2020).

4.3.2. Current Incidence as Well as Future Incidence

The actionable instructions on climate-smart agriculture coded the present incidence of cleaner production techniques 44 times and the future incidence 65 times. This suggests that the practical recommendations encourage more environmentally friendly production methods in both the present and the future. As a result, practices that do not support sustainable practices, integrated soil fertility management, local involvement, natural resource management, and livestock management techniques must be stopped. Numerous portrayals of climate change as an existential threat highlight the necessity of encouraging environmentally friendly behavior in order to boost cleaner output. Perception of climate change as a personal threat influences the intention to take action to reduce its impacts (Ma et al., 2023).

4.3.3. Actuation in Practice and Non-practice

The practical methods to embrace cleaner production are outlined in the climate-smart agricultural actionable guidelines. Practice actuation and non-practice actuation were tagged 76 and 25 times, respectively, from the actionable recommendations. The many phases for implementing cleaner production were discussed, but other cleaner practices were enumerated without any concrete measures to illustrate them. Cleaner production methods can be implemented using the practice and non-practice actions that are suggested in the actionable guidelines. According to Abunyewah et al. (2020), information about climate mitigation must be useful, accessible, inclusive, comprehensive, and integrate indigenous and scientific knowledge that examines cultural, social, and value systems.

5. Conclusions

This study's content examined practical recommendations for implementing climate-smart agriculture in South Africa in relation to cleaner production methods, as well as how to frame and style communication within agroecological principles. The practical guidelines address the key cleaner production methods of inputs, synergy, social values, and land and national government. Synergy, fairness, governance, animal health, and recycling are among the cleaner production practices that have the highest frequency of codes, in decreasing order, according to the content analysis of actionable guidelines on climate-smart agriculture. In contrast, social values, knowledge co-creation, and inputs are among the practices that have the highest frequency of responses.

Droughts, low productivity, and poor resilience are some of the repercussions of climate change that would worsen if clean production techniques were not mandated by the rules.
The actionable guidelines are supposed to encourage cleaner production methods in both the present and the future. This means that practices that do not align with sustainable practices, integrated soil fertility management, local participation, natural resource management, and livestock management practices must be suspended. The practical methods to embrace cleaner production are outlined in the climate-smart agriculture actionable guidelines. While several cleaner practices were given without any concrete procedures for proof, the various stages of implementing cleaner production were presented. These findings have implications for future and existing incidence, practice actuation and non-practice actuation, and treatment-induced and efficacy-induced communication connected to cleaner manufacturing practices.

CRediT Author Statement: This is a single author paper and the author was solely responsible for the content, including the concept, design, analysis, writing, and revision of the manuscript.

Data Availability Statement: The data for this study is available upon request.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

Acknowledgments: Not applicable.

References

Abunyewah, M., Gajendran T., Maund, K., & Okyere, S. A. (2020). Strengthening the information deficit model for disaster preparedness: Mediating and moderating effects of community participation. *International Journal of Disaster Risk Reduction*, *46*, 101492. https://doi.org/10.1016/j.ijdrr.2020.101492

Averchenkova, A., Gannon, K. E., & Curran, P. (2019). *Governance of climate change policy: A case study of South Africa*. Grantham Research Institute on Climate Change and the Environment & Centre for Climate Change Economics and Policy. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2019/06/GRI_Governance-of-climate-change-policy_SA-case-study_policy-report_40pp.pdf

Bhattacharyya, S. S., Leite, F. F. G. D., Adeyemi, M. A., Sarker, A. J., Cambareri, G. S., Faverin, C., Tieri, M. P., Castillo-Zacarías, C., Melchor-Martínez, E. M., Iqbal, H. M. N., & Parra-Saldívar, R. (2021). A paradigm shift to CO_2 sequestration to manage global warming – With the emphasis on developing countries. *Science of The Total Environment*, *790*, 148169. https://doi.org/10.1016/j.scitotenv.2021.148169

Boakye, G. O., Wiafe, J. O., & Frimpong, F. (2023). Barriers to climate change communications. *Ghana Journal of Geography*, *15*(3), 1–25. https://www.ajol.info/index.php/gjg/article/view/261603

Branca, G., & Perelli, C. (2020). 'Clearing the air': Common drivers of climate-smart smallholder food production in Eastern and Southern Africa. *Journal of Cleaner Production*, *270*, 121900. https://doi.org/10.1016/j.jclepro.2020.121900

Chen, J., Wang, G., Hamani, A. K. M., Amin, A. S., Sun, W., Zhang, Y., Liu, Z., & Gao, Y. (2020). Optimization of nitrogen fertilizer application with Climate-Smart Agriculture in the North China Plain. *Water*, *13*(23), 3415. https://doi.org/10.3390/w13233415

Davis, K. E., Babu, S. C., & Ragasa, C. (2020). *Agricultural extension: Global status and performance in selected countries*. International Food Policy Research Institute. https://doi.org/10.2499/9780896293755

Dawson, J., Carter, N., van Luijk, N., Parker, C., Weber, M., Cook, A., & Provencher, J. (2020). Infusing Inuit and local knowledge into the Low Impact Shipping Corridors: An adaptation to increased shipping activity and climate change in Arctic Canada. *Environmental Science & Policy*, *105*, 19–36. https://doi.org/10.1016/j.envsci.2019.11.013

Dong, H., Zhang, Y., & Chen, T. (2023). A study on farmers' participation in environmental protection in the context of rural revitalization: The moderating role of policy environment. *International Journal of Environmental Research and Public Health*, *20*(3), 1768. https://doi.org/10.3390/ijerph20031768

Donlon, M. (2023, May 19). *Communicating climate change: Science, solutions, solidarity*. World Meteorological Organization https://wmo.int/media/magazine-article/communicating-climate-change-science-solutions-solidarity

Doyle, J. (2022). Communicating climate change in 'Don't Look Up.' *Journal of Science Communication*, *21*(05). https://doi.org/10.22323/2.21050302

Duan, Z., Li, J., Li, F., Ding, J., Jiang, Y., Liu, J., & Zhang, W. (2024). Building smallholder-adapted climate-resilient systems: Evidence from China's apple farms. *Journal of Cleaner Production*, *435*, 140303. https://doi.org/10.1016/j.jclepro.2023.140303

England, M. I., Dougill, A. J., Stringer, L. C., Vincent, K. E., Pardoe, J., Kalaba, F. K., Mkwambisi, D. D., Namaganda, E., & Afionis, S. (2018). Climate change adaptation and cross-sectoral policy coherence in southern Africa. *Regional Environmental Change*, *18*, 2059−2071. https://doi.org/10.1007/s10113-018-1283-0

Evans, H.-C., Dyll, L., & Teer-Tomaselli, R. (2018). Communicating climate change: Theories and perspectives. In W. Leal Filho, E. Manolas, A. M. Azul, U. M. Azeiteiro, & H. McGhie (Eds.). *Handbook of Climate Change Communication: Vol. 1: Theory of Climate Change Communication* (pp. 107–122). Springer Cham. https://doi.org/10.1007/978-3-319-69838-0_7

Food and Agriculture Organization of the United Nations. (2021). *Strengthening the enabling environment for Responsible Investment in Agriculture and Food Systems – Evidence from Sierra Leone.* https://www.fao.org/3/cb2228en/CB2228EN.pdf

Fet, A. M., Haskins, C., & Sparrevik, M. (2023). Input-output analysis and cleaner production. In A. M. Fet (Ed.), *Business transitions: A path to sustainability* (pp. 37−43). Springer Cham. https://doi.org/10.1007/978-3-031-22245-0_4

Glassman, S. I., Weihe, C., Li, J., Albright, M. B. N., Looby, C. I., Martiny, A. C., Treseder, K. K., Allison, S. D., & Martiny, J. B. H. (2018). Decomposition responses to climate depend on microbial community composition. *Proceedings of the National Academy of Sciences*, *115*(47), 11994−11999. https://doi.org/10.1073/pnas.1811269115

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, *377*(1−2), 80−91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Hennink, M., Hutter, I., & Bailey, A. (2019). *Qualitative research methods*. Sage. https://uk.sagepub.com/sites/default/files/upm-assets/114917_book_item_114917.pdf

High Level Panel of Experts on Food Security and Nutrition. (2019). *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition*. https://agritrop.cirad.fr/604473/1/604473.pdf

Hilmi, Y. S., Tóth, J., Gabnai, Z., Király, G., & Temesi, Á. (2024). Farmers' resilience to climate change through the circular economy and sustainable agriculture: A review from developed and developing countries. *Renewable Agriculture and Food Systems*, *39*, Article e15. https://doi.org/10.1017/S1742170524000097

Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis, the working group I contribution to the sixth assessment report*. https://doi.org/10.1017/9781009157896

Jimenez-Lopez, C., Fraga-Corral, M., Carpena, M., García-Oliveira, P., Echave, J., Pereira, A. G., Lourenço-Lopes, C., Prieto, M. A., & Simal-Gandara, J. (2020). Agriculture waste valorisation as a source of antioxidant phenolic compounds within a circular and sustainable bioeconomy. *Food & Function*, *11*(6), 4853−4877. https://doi.org/10.1039/D0FO00937G

Kalogiannidis, S., & Syndoukas, D. (2024). The impact of agricultural extension services on farm output: A worldwide viewpoint. *Research on World Agricultural Economy*, *5*(1), 96–114. https://doi.org/10.36956/rwae.v5i1.999

Kurdyś-Kujawska, A., Strzelecka, A., & Zawadzka, D. (2021). The impact of crop diversification on the economic efficiency of small farms in Poland. *Agriculture*, *11*(3), 250. https://doi.org/10.3390/agriculture11030250

Lee, B. Y., Pavilonis, B., John, D. C., Heneghan, J., Bartsch, S. M., & Kavouras, I. (2024). The need to focus more on climate change communication and incorporate more systems approaches. *Journal of Health Communication*, *29*(sup1), 1–10. https://doi.org/10.1080/10810730.2024.2361566

Ma, X., Yang, Y., & Chen, L. (2023). Promoting behaviors to mitigate the effects of climate change: Using the extended parallel process model at the personal and collective level in China. *Environmental Communication*, *17*(4), 353–369. https://doi.org/10.1080/17524032.2023.2181134

Maibach, E. W., Uppalapati, S. S., Orr, M., & Thaker, J. (2023). Harnessing the power of communication and behavior science to enhance society's response to climate change. *Annual Review of Earth and Planetary Sciences*, *51*, 53–77. https://doi.org/10.1146/annurev-earth-031621-114417

Mburu, M., Mburu, J., Nyikal, R., Mugera, A., & Ndambi, A. (2024). Role of agricultural extension in learning for uptake and intensification of less-practiced dairy climate-smart practices in Kenya. *Cogent Food & Agriculture*, *10*(1). https://doi.org/10.1080/23311932.2024.2330182

Mnkeni, P. N. S., Mutengwa, C. S., Chiduza, C., Beyene, S. T., Araya, T., Mnkeni, A. P., Eiasu, B., & Hadebe, T. (2019). *Actionable guidelines for the implementation of climate smart agriculture in South Africa. Volume 2: Climate Smart Agriculture Practices.* Department of Environment, Forestry and Fisheries, Republic of South Africa. https://www.dffe.gov.za/sites/default/files/docs/csa_volume2.pdf(open in a new window).

Mujeyi, A., Mudhara, M. & Mutenje, M. The impact of climate smart agriculture on household welfare in smallholder integrated crop-livestock farming systems: Evidence from Zimbabwe. *Agriculture & Food Security*, *10*, 4. https://doi.org/10.1186/s40066-020-00277-3

Penz, H. (2022). Communicating climate change: How (not) to touch a cord with people and promote action. *Text & Talk*, *42*(4), 571–590. https://doi.org/10.1515/text-2020-0081

Peters, E., Boyd, P., Cameron, L. D., Contractor, N., Diefenbach, M. A., Fleszar-Pavlovic, S., Markowitz, E., Salas, R. N., & Stephens, K. K. (2022). Evidence-based recommendations for communicating the impacts of climate change on health. *Translational Behavioral Medicine*, *12*(4), 543–553. https://doi.org/10.1093/tbm/ibac029

Poortvliet, P. M., Niles, M. T., Veraart, J. A., Werners, S. E., Korporaal, F. C., & Mulder, B. C. (2020). Communicating climate change risk: A content analysis of IPCC's summary for policymakers. *Sustainability*, *12*(12), 4861. https://doi.org/10.3390/su12124861

Principles for Responsible Investment. (2020). *From farm to table: Ensuring fair labour practices in agricultural supply chains: Results from the PRI collaborative engagement 2017–19*. https://www.unpri.org/download?ac=10533

Saifan, S., Shibli, R., Ariffin, I. A., Ab Yajid, M. S., & Tham, J. (2021). Climate change and extension services' effects on farm level income in Malaysia: A time series analysis. *AgBioForum*, *23*(2), 72–81. https://agbioforum.org/menuscript/index.php/agb/article/view/63/42

Santoso, A., Taschetto, A. S., McGregor, S., Roxy, M. K., Chung, C., Wu, B., & Delage, F. P. (2023). Editorial: Dynamics and impacts of tropical climate variability: Understanding trends and future projections. *Frontiers in Climate*, *5*. https://doi.org/10.3389/fclim.2023.1148145

Shi, L., Liu, J., Wang, Y., & Chiu, A. (2021). Cleaner production progress in developing and transition countries. *Journal of Cleaner Production*, *278*, 123763. https://doi.org/10.1016/j.jclepro.2020.123763

Shin, D., Curtis, M., Huisingh, D., & Zwetsloot, G. I. (2008). Development of a sustainability policy model for promoting cleaner production: A knowledge integration approach. *Journal of Cleaner Production*, *16*(17), 1823–1837. https://doi.org/10.1016/j.jclepro.2008.06.006

Singh, S., Kumar, V., Singh, S., Dhanjal, D. S., Datta, S., & Singh, J. (2020). Global scenario of plant–microbiome for sustainable agriculture: Current advancements and future challenges. In A. Yadav, J. Singh, A. Rastegari, & N. Yadav (Eds.), *Plant microbiomes for sustainable agriculture* (pp. 425–443). Springer Cham. https://doi.org/10.1007/978-3-030-38453-1_14

Sippel, M., Shaw, C., & Marshall, G. (2022). *Ten key principles: How to communicate climate change for effective public engagement.* Climate Outreach Working Paper. https://doi.org/10.2139/ssrn.4151465

Tsangas, M., Gavriel, I., Doula, M., Xeni, F., & Zorpas, A. A. (2020). Life cycle analysis in the framework of agricultural strategic development planning in the Balkan region. *Sustainability*, *12*(5), 1813. https://doi.org/10.3390/su12051813

Villalba-Eguiluz, U., Sahakian, M., González-Jamett, C., & Etxezarreta, E. (2023). Social and solidarity economy insights for the circular economy: Limited-profit and sufficiency. *Journal of Cleaner Production*, *418*, 138050. https://doi.org/10.1016/j.jclepro.2023.138050

Wang, S., Hurlstone, M. J., Leviston, Z., Walker, I., & Lawrence, C. (2019). Climate change from a distance: An analysis of construal level and psychological distance from climate change. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.00230

Wang, Z., Fu, H., & Ren, X. (2023). Political connections and corporate carbon emission: New evidence from Chinese industrial firms. *Technological Forecasting and Social Change*, *188*, 122326. https://doi.org/10.1016/j.techfore.2023.122326

Waters, Y. L., Wilson, K. A., & Dean, A. J. (2024). The role of iconic places, collective efficacy, and negative emotions in climate change communication. *Environmental Science & Policy*, *151*, 103635. https://doi.org/10.1016/j.envsci.2023.103635

World Wide Fund For Nature (WWF). (2021). *Farming with biodiversity: Towards nature-positive production at scale*. https://wwfint.awsassets.panda.org/downloads/farming_with_biodiversity_towards_nature_positive_production_at_scale.pdf

Wulandari, S. (2022). Scenario development of implementing cleaner production on pepper agroindustry. *IOP Conference Series: Earth and Environmental Science*, *950*, 012048. https://doi.org/10.1088/1755-1315/950/1/012048

Yanfika, H., Effendi, I., Sumaryo, & Ansari, A. (2024). The role of agricultural extension services on supporting circular bioeconomy in Indonesia. *Frontiers in Sustainable Food Systems*, *8*. https://doi.org/10.3389/fsufs.2024.1428069

Yusuf, J.-E. W., & St John, B., III. (Eds.). (2021). *Communicating Climate Change*. Routledge. https://doi.org/10.4324/9781003037378

Open Call for Papers

Bridging disciplines such as economics, sociology, and human geography, Agricultural & Rural Studies (**A&R, ISSN 2959-9784**) is a double-blind peer-reviewed international journal that fosters high-impact research connecting theoretical innovation with empirical depth, ultimately supporting evidence-based solutions for sustainable and equitable futures in agriculture and rural communities worldwide.

Aims

A&R seeks to:

- Foster critical dialogue on contemporary challenges and opportunities in agriculture and rural contexts, from local to global scales.
- Promote methodologically robust research—encompassing quantitative, qualitative, and mixed approaches—that generates actionable insights for academia, policymakers, and practitioners.
- Highlight interdisciplinary perspectives to address complex issues at the intersection of agrarian systems, rural societies, and policy frameworks.
- Amplify diverse voices, ensuring representation of marginalized regions, communities, and stakeholders in scholarly discourse.

Scope

A&R prioritizes, but is not confined to, research that engages with the following thematic areas:

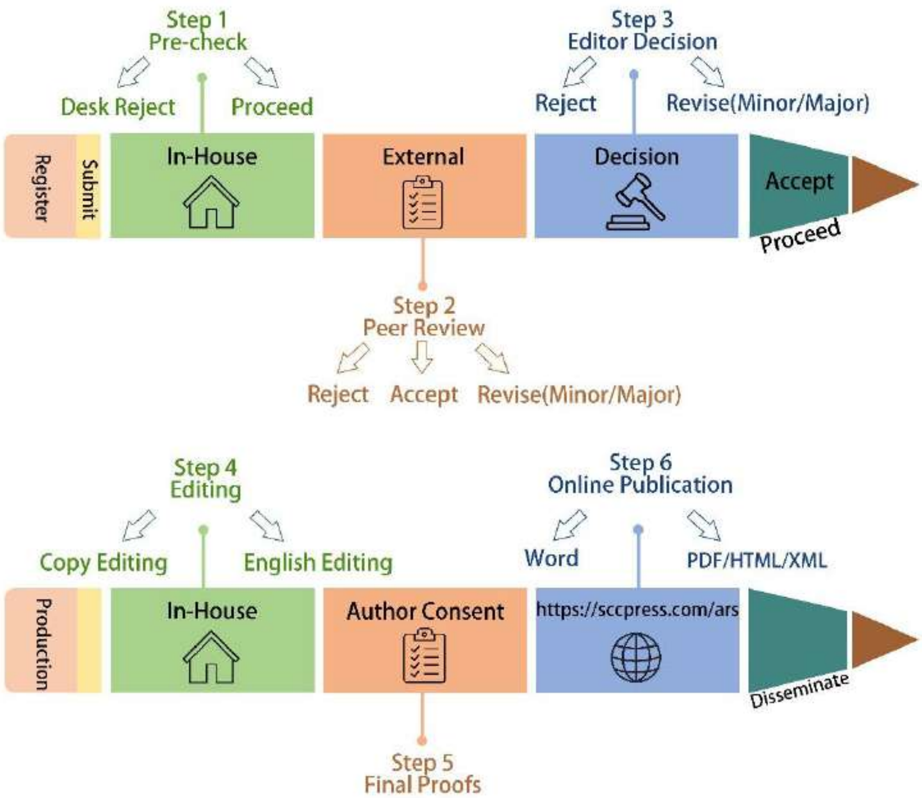
- Agricultural Systems & Sustainability: Studies on sustainable farming practices, agroecology, climate resilience, and the environmental, social, and economic dimensions of agricultural production and food systems.
- Rural Development & Livelihoods: Analyses of rural economic transformations, poverty alleviation strategies, rural-urban linkages, and the socio-cultural dynamics of rural communities.
- Farmer Well-being & Equity: Investigations into farmer agency, gender and social inclusion, labor dynamics, and the impacts of policies on rural households and vulnerable groups.
- AI Innovation & Technology: Research on smart agriculture, precision farming, rural e-commerce, and the socio-institutional implications of AI tools for agricultural and rural development.
- Policy & Governance: Evaluations of agricultural and rural policy frameworks, institutional arrangements, and regulatory mechanisms, with attention to their

effectiveness, equity, and adaptability across contexts.

- Emergent Challenges & Opportunities: Explorations of transformative trends—from biotechnological advancements to climate adaptation—to understand their potential to reshape agricultural and rural futures.

A&R prioritizes empirical research that connects localized insights to broader theoretical or policy debates, as well as critical reviews, case studies, and methodological innovations. All submissions undergo rigorous peer review to ensure scholarly excellence, relevance, and clarity. By bridging discipline boundaries and fostering global dialogue, **A&R** aims to be a cornerstone of interdisciplinary scholarship in agricultural and rural studies.

We cordially invite authors to submit original, previously unpublished manuscripts for consideration in **A&R**. All submissions should be made via our online submission system at https://sccpress.com/ars.



To Be

a Leading Academic Journal
at the Nexus of
Agricultural Sustainability,
Rural Revitalization & Farmer Well-Being.

Agricultural & Rural Studies

Abstracted & Indexed in: Crossref; Dimension; Google Scholar; J-Gate.

Publisher
SCC PRESS, Unit 811, Beverley Commercial Centre,
87-105 Chatham Road South, Tsim Sha Tsui,
Kowloon, Hong Kong S.A.R., China.

Editorial Office
Rural Revitalization Academy of Zhejiang Province,
Zhejiang A&F University, Hangzhou, Zhejiang,
311300, China.

Editorial Assistants
Travis Malone (travismalone@sccpress.com)
Grace Li (grace@sccpress.com)
Rui Zhang (ruizhang@sccpress.com)

Photographer
Aleksandar Čučković

Layouter
Tao He

SCC PRESS
Academic OA Publishing
Began in 2023