

ORIGINAL ARTICLES

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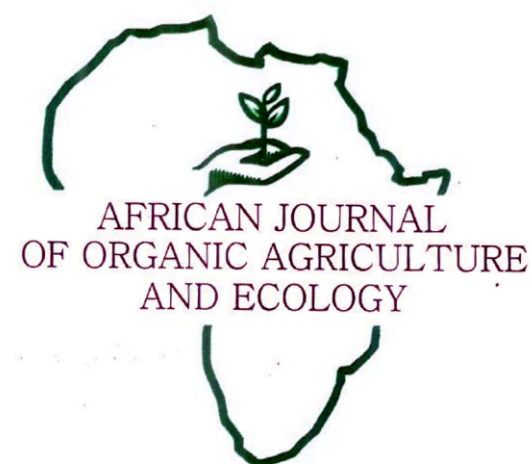
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Network of Organic Agriculture Researchers in Africa
RÉSEAU DES CHERCHEURS EN AGRICULTURE BIOLOGIQUE EN AFRIQUE
شبكة الباحثين في الزراعة العضوية بإفريقيا
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ABOUT NOARA

The Network of Organic Agriculture Researchers in Africa (NOARA) was established to unite and coordinate African organic and ecological agriculture scientific and technical researchers within and outside Africa. The network is an African initiative. NOARA is a network independently established by African organic researchers that met at Modena, Italy, in 2005 but was later launched in 2009, during the 1st African Organic Conference in Kampala. During the 2nd African Organic Conference (2nd AOC) held in Lusaka, Zambia, in May 2012, a side event brought together participants from almost all regions of Africa and Europe to discuss how to develop organic agriculture research agenda. Research was underscored as a critical component of any initiative designed to promote ecologically sustainable development of agriculture in Africa. The 4th AOC in 2018 General Assembly at Saly, Senegal, recommended AfrONet to revive NOARA and probably re-organize the Network for effectiveness in its expected roles. A Coordinator was therefore appointed in March 2019 to build NOARA and ensure proper functionality of the Network.

NOARA VISION

Africa with zero hunger, poverty eradicated, improved livelihoods and sustained ecosystem through innovative organic and ecological agriculture research.

NOARA MISSION

To generate and disseminate sound evidence-based scientific organic agricultural knowledge that can ensure healthy, ecological, fairness and care of organic agriculture actors in Africa for sustainable livelihood and ecosystem, leading to food security, incomes and sustainable development.

NOARA SPECIFIC OBJECTIVES AND RESEARCH PRIORITIES

Thematic area 1: Research and Training

- Lead research agendas on organic and ecological agriculture in Africa.
- Coordinate organic and ecological agriculture training and research in Africa.
- Support or initiate research activities that will contribute to the social, cultural and economic



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productivity of Africa's smallholder farmers, processors and marketers, particularly, women and youths who have been largely marginalized.

- Demonstrate success stories useful for up scaling organic and ecological agricultural practices.

Thematic area 2: Policy and Stakeholders' Engagements

- Promote collaboration among organic and ecological agriculture researchers, practitioners, farmers and policy makers in Africa.
- Foster improved ecological organic agriculture database, to influence policy development in Africa.
- Advocate for the mainstreaming of organic and ecological agriculture into agricultural research and innovation to enhance food security in Africa.
- Engage organizations producing organic and ecological inputs in confirmatory and adaptive research for possible recommendation of their products to end users in Africa and beyond.

Thematic area 3: Conferences and Information Dissemination

- Organize conferences and meetings for the exchange of information on organic and ecological agriculture.
- Publish research and technical results on organic and ecological agriculture.
- Organise consortia of experts to address specific or emerging issues relating to organic and ecological agriculture in Africa.

Thematic area 4: Networking, Advocacy and Awards

- Enhance partnerships for organic and ecological agriculture research in Africa and beyond.
- Map out like-minded organisations.
- Honour distinguished members as fellows of the network.
- Represent the interest of organic and ecological agriculture researchers within and beyond Africa.



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NOARA KEY SERVICES

NOARA shall undertake functions appropriate to meeting the objectives cited in this constitution including to: (within and outside Africa)

- Undertake lobbying and advocacy on organic and ecological agriculture research at high levels.
- Support capacity building for key players in organic and ecological agriculture across the continent.
- Mobilize resources for NOARA's endeavours in promoting organic agriculture on the continent.
- Spearhead organic agriculture research, extension, training and value chains and market development.
- Provide management and administrative consultancy to like-minded programmes and partners on organic agriculture research; and,
- Undertake any other functions as deemed necessary to address NOARA's objectives.

The functions of the Network shall be conducted as much as possible by pooling and making use of members' own human, financial and technical resources. However, NOARA shall also make concerted effort to mobilize resources at various levels (local, national, regional, continental and international) to support research and networking activities, for a vibrant and successful Network.

Membership

NOARA is a membership Network that draws members from national, regional, continental and international organic agriculture organisations, associations, networks and companies within and outside Africa, but whose aims and goals are in support of organic and ecological agriculture.

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Contributions may be on Agricultural Economics, Agricultural Engineering, Agricultural Extension, Agroforestry, Animal science, Crop/Environmental protection, Crop science, Environmental Sciences, Fishery/Aquaculture, Pharmacy, Soil science, Veterinary Medicine, Wildlife Management. Careful editing and scrutiny are required before sending manuscript to the editor as no room for alteration may exist once an article is accepted for publication based on reviewers' comments. Contributors are to send their manuscripts, not previously published or being considered for publication elsewhere to:

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IMPLICATION DES FEMMES ET DES JEUNES EN AGRECOLOGIE: CAS DE L'ASSOCIATION NOURRIR SANS DETRUIRE (ANSD) DU BURKINA FASO e Published: July, 2026

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Résumé

L'implication des femmes et des jeunes en agroécologie est cruciale pour la durabilité et la résilience des systèmes agricoles. Les femmes, représentant 60-70 % de la main-d'œuvre agricole, jouent un rôle important dans la production alimentaire, mais leur travail reste souvent invisible. L'ANSD s'engage à valoriser sa contribution à travers diverses actions.

La stratégie adoptée comprend le renforcement de l'accès aux ressources, le leadership féminin, l'autonomisation des femmes, l'éducation environnementale pour les jeunes et la prise en compte des ménages vulnérables. Pour sensibiliser et éduquer, des ateliers d'information sont organisés, ainsi que des programmes de formation sur des compétences pratiques comme le jardinage et l'élevage durable.

Le renforcement des capacités passe par la mise en place de formations adaptées aux besoins des femmes et des jeunes, ainsi que leur participation active à des programmes de recherche. La création de groupes d'épargne permet aux femmes d'accéder à des fonds pour investir dans des pratiques agroécologiques et d'échanger des connaissances.

L'accès à la terre et aux intrants reste un défi majeur, avec seulement 8% des terres agricoles détenues par des femmes. L'ANSD aide à surmonter ces obstacles en facilitant l'accès à la terre et aux ressources nécessaires. De plus, il est essentiel d'inclure les femmes et les jeunes dans les comités de gestion et de promouvoir des politiques favorisant l'égalité des sexes. En somme, l'engagement des femmes et des jeunes en agroécologie est fondamental pour un développement rural inclusif et durable. Une approche holistique, combinant sensibilisation, formation, accès aux ressources et participation à la prise de décision, est nécessaire pour renforcer leur rôle et assurer un avenir résilient pour les communautés rurales.

Abstract

The involvement of women and youth in agroecology is crucial for the sustainability and resilience of agricultural systems. Women, representing 60-70% of the agricultural workforce, play a significant role in food production, yet their work often remains invisible. The ANSD (National Agency for Sustainable Development) is committed to recognizing and valuing their contribution through various initiatives. The adopted strategy includes strengthening access to resources, promoting women's leadership and empowering women, providing environmental education for young people, and addressing the needs of vulnerable households. To raise awareness and educate, information workshops are organized, along with training programs on practical skills such as gardening and sustainable livestock farming. Capacity building is achieved through the implementation of training programs tailored to the needs of women and youth, as well as their active participation in research programs. The creation of savings groups allows women to access funds to invest in agroecological practices and to share knowledge. Access to land and inputs remains a major challenge, according to the FAO Burkina Faso fact sheet, less than 6% of women are land owners. The ANSD helps overcome these obstacles by facilitating access to land and the necessary resources. Furthermore, it is essential to include women and youth on management committees and to promote gender equality policies. In short, the engagement of women and youth in agroecology is fundamental to inclusive and sustainable rural development. A holistic approach, combining awareness-raising, training, access to resources, and participation in decision-making, is necessary to strengthen their role and ensure a resilient future for rural communities.

Introduction

Femmes représentent une part importante de la main-d'œuvre agricole, souvent jusqu'à 60-70 %, et sont responsables de nombreuses tâches agricoles comme la sélection des semences, le tri des récoltes, le maraîchage, le semis, le désherbage et la récolte (FAO). Elles jouent ainsi un rôle central dans la production alimentaire locale.

En agroécologie, les femmes ne sont pas seulement productrices, elles participent aussi à la transmission des savoirs, à l'organisation collective et à la valorisation de pratiques durables qui préservent la biodiversité. Leur travail est souvent sous valorisé et l'accès aux ressources demeure un véritable défi pour elles, mais ANSD à travers son approche et ses stratégies contribue à rendre ce travail visible et à renforcer leur accès aux ressources. Ses actions visent à améliorer l'accès des femmes et des jeunes à la terre et au bio intrants, à promouvoir le leadership féminin, et à favoriser l'éducation environnementale, tout en prenant en compte les besoins des ménages vulnérables. Cet

article présente la méthodologie adoptée, les résultats obtenus, ainsi qu'une discussion sur l'impact de ces initiatives et des recommandations.

I. Méthodologie ou méthode

- " Renforcement de l'accès aux femmes aux facteurs de production
- " Renforcement du leadership féminin
- " Implication active des femmes aux différentes activités (Représentativité à travers le système de quota);
- " Animation de séances d'éducation environnementale au profit des plus jeunes
- " Prise en compte des différentes catégories des ménages en particulier les ménages vulnérables lors des ciblage des bénéficiaires (ménages gérés par des femmes etc.)
- " Diagnostic participatif et initial avant le lancement des projets permettant de prendre en compte les besoins spécifiques des femmes et couchés vulnérables.



Figure 1 : Stratégie d'implication des femmes et des jeunes

II. Résultats
1. Sensibilisation et formation des jeunes sur les pratiques agroécologiques

L'ANSD a initié un programme de formation et de sensibilisation qui vise à approfondir la compréhension des jeunes sur l'agroécologie et à encourager leur engagement dans cette démarche. Des sessions de démonstration et de partage d'expérience sont régulièrement organisées au sein des établissements d'enseignement supérieur et secondaire. Dans le cadre de ce programme, 12 jeunes ont été sélectionnés pour réaliser des vidéos sur l'agroécologie, après avoir suivi une formation sur le montage audiovisuel. Ces vidéos sont ensuite diffusées sur des plateformes numériques telles que WhatsApp et Facebook, permettant une large circulation des connaissances. En outre, des projections vidéo sont organisées dans les écoles, accompagnées d'échanges directs avec des

techniciens et des experts en agroécologie. Grâce à ces initiatives, 3850 jeunes ont été sensibilisés aux avantages de l'agroécologie à travers des ateliers d'information, soutenus par le programme Jeunes Reporters. Pour favoriser l'adoption des pratiques agroécologiques, des jardins scolaires ont été établis dans 12 écoles, où les élèves se réunissent pour participer à des activités de production de légumes, intégrant ainsi ces produits dans la préparation de leurs repas. Cette approche pratique renforce l'engagement des jeunes tout en leur offrant des compétences concrètes en agroécologie.



Photo 1 : Des élèves produisant du compost pour leur jardin scolaire

2. Renforcement des capacités techniques et organisationnelles des femmes

Formations Techniques : Un programme de formation a été mis en place, spécifiquement conçu pour répondre aux besoins des femmes et des jeunes. Ce programme met l'accent sur des compétences pratiques, notamment la production de produits maraîchers agroécologiques à travers des jardins de case, des sites maraîchers et le maraîchage hors sol ainsi que sur l'élevage durable à travers un système de dons rotatifs d'animaux. Pour la production maraîchère, des superficies d'au moins 1 hectare sont négociées dans les villages, aménagées et parcellées au profit des femmes. Avant le lancement des activités de production, celles-ci reçoivent une formation sur les techniques de production de biopesticides et de biofertilisants, qui seront exclusivement utilisés pour le traitement des cultures sur le site.

Concernant le système de dons rotatifs d'animaux, des chèvres sont attribuées aux femmes identifiées comme vulnérables dans les villages. Après la mise basse des chèvres, les jeunes animaux sont transférés à d'autres femmes, créant ainsi un cycle de partage et de soutien. Les bénéficiaires de ces chèvres sont également formés sur les techniques de fauche et de conservation du fourrage, afin d'optimiser la gestion de leurs animaux. Grâce à ces animaux, les femmes peuvent également valoriser les déjections pour la production de compost, contribuant ainsi à une agriculture durable et à l'amélioration de leurs pratiques agricoles.

Programmes de Formation: Les femmes sont activement impliquées dans les sessions de formation sur les techniques agroécologiques et la gestion des ressources naturelles. Elles sont également présentes dans le groupe des Paysans formateurs, favorisant ainsi l'échange de savoirs. De plus, leur engagement dans le

programme de recherche permet la cocréation et le partage des connaissances, avec des femmes sélectionnées pour mener des tests sur des parcelles d'expérimentation.

Entrepreneuriat et compétence de vie : L'ANSD a créé plus de 110 groupes de femmes dédiés à la transformation des produits agricoles et forestiers non ligneux. Ces groupes bénéficient d'un soutien technique de l'ANSD, qui inclut des formations sur la transformation, la commercialisation, ainsi que l'équipement nécessaire, et facilite les mises en relation avec des consommateurs et des revendeurs. Par ailleurs, des formations spécifiques ont été mises en place pour développer des compétences en négociation, en gestion de l'environnement quotidien et en gestion financière. Ainsi, 1800 femmes ont été accompagnées dans diverses activités génératrices de revenus (AGR), renforçant leur autonomie économique. Grâce à un

programme de formation technique, 16 620 femmes ont été formées aux pratiques agroécologiques, tandis que 720 d'entre elles ont activement participé à des tests et à la réplication des formations sur le terrain. De plus, 158 femmes ont été identifiées comme leaders, ce qui a consolidé leur rôle au sein de la communauté. Dans ce cadre, nous souhaitons partager l'histoire de SagdouPotiaga, qui réside à Kodjina, dans le village de Bilanga, à l'est du Burkina Faso. Cultivatrice depuis de nombreuses années, elle se sentait découragée face à une terre improductive. "Avant, chaque saison était une épreuve," confie-t-elle. Tout a changé lorsqu'elle a découvert la technique du zaï, enseignée par Logtori, un paysan formateur du projet IAE. Grâce à cette méthode, elle a revitalisé sa parcelle, permettant au maïs et au mil de prospérer. Aujourd'hui, Potiama parvient à nourrir sa famille convenablement, vend des produits sur le marché et a même pu acheter des moutons. Elle exprime sa profonde gratitude envers le projet IAE et Logtori pour leur précieux soutien.



Photo 2 : séance de formation des femmes sur la production de bio intrant Bokashi

3. Mise en place des groupes de solidarité et d'entraide

La création de **200 groupes d'épargne et de crédit** a permis de faciliter l'accès des femmes au crédit, leur offrant ainsi des opportunités d'investir dans des pratiques agroécologiques. Ces groupes servent également de plateforme pour l'échange de connaissances sur les techniques durables.

4. Renforcement de l'accès aux ressources

- * **L'accès à la terre:** ANSD accompagne les femmes à obtenir des terres sécurisées pour leur activités de production et de commercialisation.
- * **L'accès aux intrants:** Aider les femmes et les jeunes à accéder à des intrants agricoles, tels que des semences, des outils, pour leur permettre de mettre en œuvre des pratiques agroécologiques.

L'acquisition de **plus de 45 hectares de terre** au profit des femmes a été une avancée significative, permettant à celles-ci de sécuriser leurs activités de production et de commercialisation. Cependant, il reste un défi majeur, car seulement 8% des terres agricoles sont détenues par des femmes.

5. Participation à la prise de décision

La participation des femmes aux prise de décision se traduit par la représentation des femmes et des jeunes dans les comités de gestion des ressources, les comités agroécologiques et les instances décisionnelles au niveau local a été renforcer à travers un système de quotas mis en place. Au total 158 femmes ont pu intégrer des organisations locales grâce à cette démarche. Nous organisons également des cadres d'échanges avec les autorités locales et communales pour identifier les défis et les actions favorisant un accès équitable à la terre. A ce titre nous accompagnons les communes à élaborer des plans de résiliences sensibles au genre.



Photo 3 : Formation des femmes sur le leadership et le management

III. Discussion

Les résultats soulignent l'impact positif des initiatives de l'ANSD sur l'autonomisation des femmes et des jeunes dans le secteur agroécologique. L'accès accru à la terre et aux ressources a permis de renforcer la résilience des ménages, tandis que la formation et la sensibilisation ont favorisé une prise de conscience accrue des enjeux liés à l'agroécologie. La création de groupes d'épargne a également été un moteur d'autonomisation, permettant aux femmes d'investir dans leurs activités agricoles. Cependant, des défis persistent, notamment l'accès limité aux intrants et la nécessité d'une représentation plus forte des femmes dans les instances décisionnelles. Il est essentiel de continuer à promouvoir des politiques favorisant l'égalité des sexes et d'assurer un soutien continu aux initiatives d'autonomisation.

IV. Recommandations

our garantir une pérennité des résultats obtenus et renforcer le rôle des femmes et des jeunes en agroécologie, plusieurs recommandations peuvent être formulées :

- * Promouvoir des politiques permettant aux femmes d'acquérir des terres sécurisées pour leurs activités agricoles.
- * Accroître le financement des programmes d'éducation et de formation spécifiques aux femmes et aux jeunes.
- * Impliquer davantage les femmes dans les programmes de recherche pour la co-création de connaissances et le partage de bonnes pratiques.
- * Renforcer la représentation des femmes dans les instances décisionnelles et de gestion des ressources agricoles.
- * Organiser des campagnes de plaidoyer pour sensibiliser les décideurs sur l'importance de l'égalité des sexes dans le secteur agricole.



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Conclusion:

En conclusion, l'engagement des femmes et des jeunes en agroécologie est un facteur déterminant pour la durabilité et la résilience des systèmes agricoles. Des efforts continus sont nécessaires pour surmonter les obstacles existants et garantir un développement rural inclusif et durable.

Références :

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Rooting Climate Resilience with Agroecological Urbanism Charles L. Tumuhe^{1*}, Joshua Muloi ³, Denis Katusiime ⁵, David Ssekamatte ⁴, Ronald Byaruhanga ²,

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Abstract

As African cities rapidly urbanize, urban food systems face compounded challenges of climate change, environmental degradation, youth unemployment, and food insecurity. This study explores how urban agroecology, specifically through the lens of "agroecological urbanism," can contribute to climate resilience and sustainable urban transformation. Using a qualitative case study approach, the research investigates two urban agroecology hubs in Uganda's Kampala Metropolitan Area: JERO Farm and the Agency for Integrated Rural Development (AFIRD). These hubs demonstrate distinct yet complementary models. Data was collected through focus group discussions, in-depth interviews, small group interviews, field observations, and visual analysis. The findings are structured around three core themes: climate-resilient innovations, community engagement, and systemic barriers. Both hubs apply agroecology principles to adapt to urban constraints while contributing to climate adaptation and mitigation. Community participation is central to both models, strengthening social resilience and local food systems. However, issues such as insecure land tenure, high operational costs, and limited policy support continue to constrain broader adoption and institutional integration. The study calls for inclusive urban planning, creation of urban "agroecology villages", and supportive markets to enable systemic transformation.

Keywords: urban agroecology; climate resilience; permaculture.

Résumé

Face à l'urbanisation rapide des villes africaines, les systèmes alimentaires urbains sont confrontés à des défis complexes liés au changement climatique, à la dégradation de l'environnement, au chômage des jeunes et à l'insécurité alimentaire. Cette étude explore comment l'agroécologie urbaine, et plus particulièrement le concept d’urbanisme agroécologique ", peut contribuer à la résilience climatique et à une transformation urbaine durable. À travers une étude de cas qualitative, la recherche examine deux pôles d'agroécologie urbaine dans la zone métropolitaine de Kampala, en Ouganda : la ferme JERO et l'Agence pour le développement rural intégré (AFIRD). Ces pôles présentent des modèles distincts mais complémentaires. Les données ont été recueillies par le biais de discussions de groupe, d'entretiens approfondis, d'entretiens en petits groupes, d'observations de terrain et d'analyses visuelles. Les résultats s'articulent autour de trois thèmes principaux : les innovations résilientes au climat, l'engagement communautaire et les obstacles systémiques. Les deux pôles appliquent les principes agroécologiques pour s'adapter aux contraintes urbaines tout en contribuant à l'adaptation au changement climatique et à son atténuation. La participation communautaire est essentielle aux deux modèles, renforçant la résilience sociale et les systèmes alimentaires locaux. Cependant, des problèmes tels que la précarité foncière, les coûts opérationnels élevés et le soutien politique limité continuent de freiner une adoption plus large et une intégration institutionnelle. L'étude conclut en appelant à une planification urbaine inclusive, à la création de villages agroécologiques urbains et à des marchés de soutien pour permettre une transformation systémique.

Mots-clés : agroécologie urbaine ; résilience climatique ; permaculture.

Introduction

As urbanization accelerates across Africa, cities face mounting pressures of food insecurity, environmental degradation, and unemployment, particularly among youth and women. "Agroecological urbanism", thereafter referred to as urban agroecology, has emerged as a promising response, advancing sustainable food systems, community health, and ecological restoration within constrained spaces(Rudolph andMuchesa, 2024;Peano *et al.*, 2020).Despite this potential, the practice remains under-recognised in scholarship, weakly supported in policy, and unevenly implemented. Conceptual inconsistencies and the absence of standardized evaluation frameworks limit recognition of the benefits of urban agroecology and hinder identification of successful implementation drivers (Dumont *et al.*, 2021).

Much of the current literature foregrounds "urban agriculture" rather than "urban agroecology." For

example, research shows that urban agriculture could contribute 15-20% of global food supply yet structural, social, and political barriers constrain its scaling up, deep and out (Altieri *et al.*, 2025). Institutional gaps, weak educational outreach, and the lack of structured learning platforms further undermine the transformative potential for urban agroecology (Kay *et al.*, 2022). Addressing these barriers requires intentional scholarship to model environments and multi-stakeholder frameworks that can strengthen community-driven approaches and embed sustainability into urban agroecology (Bisagaet *et al.*, 2019).

However, existing scholarship has focused on rural agroecology, framed in ways that lack ecological and social justice dimensions suitable for the urban context (Siegner *et al.*, 2020; Villarino *et al.*, 2021). For instance, a study biased to rural agroecology mapped 12 experiences in San Luis Potosí, noting the limited attention given to urban contexts despite rising urban

pressures (Anzaldo Montoya andMunguía Moreno, 2025). This neglect limits recognition of urban agroecology as a transformative pathway and constrains policy innovation (Cheng *et al.*, 2022; López-García andCarrascosa-García, 2024; Rudolph, Muchesaand Kroll, 2020). Given the limited knowledge of urban agroecology, it remains difficult to address systemic challenges and foster participatory, community-based climate resilience in African cities. This study addresses these gaps by examining two Kampala-based urban agroecology hubs: JERO Farm and the Agency for Integrated Rural Development (AFIRD), members of Participatory Ecological Land Use Management (PELUM) Uganda, a charter under the 14-country PELUM Association. The study explores how the hubs integrate agroecology principles in constrained urban settings, engage diverse communities, and navigate systemic barriers. In doing so, the study contributes empirical evidence from sub-Saharan Africa and offers insights into scaling urban agroecology through enabling policies, municipal planning, and grassroots innovation.

Theoretical Framing

This study is guided by an integrated theoretical framework that combines the High Level Panel of Experts on Food Security and Nutrition (HLPE) 13 agroecology principles (Wezel *et al.*, 2020), Social-Ecological Urbanism (SEU), resilience theory, and the concept of "agroecological urbanism" to analyse sustainable urban farming initiatives as dynamic and context-specific systems. The HLPE principles provide a normative and analytical lens to assess ecological practices, social relations, and governance arrangements, particularly the principles of recycling, input reduction, biodiversity, synergies, co-creation of knowledge, fairness, and resource governance. SEU provides the overarching lens by conceptualising cities as interconnected social and ecological systems in which urban form, institutions, and discourse shape

ecological processes and social outcomes (Berghauser Pont *et al.*, 2022). Within this framing, urban agroecology is understood as a socio-ecological intervention that actively redesigns urban spaces and institutions to enhance sustainability, resilience, and social equity. Resilience theory informs the analysis by focusing on adaptive capacity, diversity, redundancy, and transformability in the face of climate and urban pressures (Folke *et al.*, 2010), while agroecological urbanism situates these processes within the spatial, infrastructural, and political realities of dense cities. Together, these perspectives enable a holistic examination of how urban agroecology contributes to climate resilience, food security, and social transformation under conditions of constraint and uncertainty. Linking agroecology innovations (adaptive practices), climate resilience (system robustness), community engagement (social resilience), and navigating challenges (system vulnerabilities), the Resilience Theory informs the following research questions.

Research Questions

- 1. How do urban agroecology innovations build climate resilience?
- 2. How do institutions engage communities in the urban agroecology innovations?
- 3. How can existing challenges in urban agroecology be addressed?

Methodology

This study employed a qualitative case study design to explore practices, innovations, and challenges of urban agroecology in the Kampala metropolitan area of Uganda. The Kampala Metropolitan Area refers to the functional urban region comprising Kampala City and the surrounding districts of Wakiso, Mukono, and Mpigi, which are interconnected through commuting, infrastructure, markets, and shared ecological systems (Uganda Bureau of Statistics and Kampala Capital City

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Authority, 2019).Two agroecology hubs were purposively selected: JERO Farm in Entebbe, a demonstration site applying agroecology principles through demonstration and farm-based learning, and the AFIRD in Nkoowe, a development organization supporting peri-urban and urban agroecology through farmer mobilisation, women and youth training, and value addition (AFIRD Uganda, 2022; JERO Farm, 2025).

JERO Farm, located in Kitala Village, Wakiso District, central Uganda, is a pioneering urban agroecology hub that showcases how small spaces can be transformed into productive, sustainable food systems. Serving as a one-stop center for agroecological training and demonstration, the farm empowers households to reconnect with food sources through hands-on practices. With over 120 extension farms, 80 women's groups, 50 farm outlets, and influence in 20 agroecology expos nationwide, JERO Farm is catalysing a shift from food consumption to food citizenship in Uganda's rapidly urbanizing landscape (JERO Farm, 2025).

AFIRD is based in Nkoowe, Wakiso district, along Kampala-Hoima Road in Uganda and has been a key driver of ecological and inclusive rural development since its founding in 1997. Officially registered as an NGO in 1998, AFIRD operates nationally, with active programs in Wakiso, Mpigi, and Mukono districts. With over 25 years of experience, it has supported 5,000+ households, trained 170+ farmer groups, and integrated ecological farming into 36+ schools. Guided by a strategic plan, AFIRD's work focuses on farmer-led development, youth empowerment, advocacy and lobbying, and institutional development, promoting sustainable livelihoods and agroecological transformation at the grassroots level (AFIRD Uganda, 2022).

The two selected hubsare members of the PELUM

network and engaged in urban agroecology. PELUM Uganda Secretariat staff guided the selection of the two hubs to participate in the study. With Secretariat guidance, we purposively selected JERO Farm and AFIRD for their contrasting institutional models: farm-based versus NGO-led. We employed a qualitative approach, an appropriate approach for capturing lived experiences and contextual dynamics in the two urban agroecology hubs (Yardley *et al.*, 2019). Data collection drew on multiple methods to ensure triangulation and credibility (Haywood and Lawlor, 2018; Rouse and Harrison, 2015). These included two focus group discussions (FGDs), three in-depth interviews (IDIs), one small group interview (SGI), field observations, photographic documentation, and informal WhatsApp exchanges. Two FGDs were conducted: one with AFIRD staff and another with JERO staff and farmers. An IDI with JERO's team leader (Richard Mugisha) focused on leadership, innovation, climate resilience, and youth engagement, complemented by two IDIs with AFIRD staff (Faizo, Youth Empowerment Program Manager, and Justine, Advocacy and Lobbying Program Manager). These interviews explored innovations, market linkages, bio-input production, and community strategies. An SGI with representatives from both hubs, JERO Farm and AFIRD (Richard, Faizo, Justine),further clarified challenges (Table 1). Observational visits to the two hubs enabled direct assessment of farming agroecological techniques, while photographs (e.g., Fig 1) provided additional empirical evidence. All FGDs, SGIs and IDIs were conducted on Zoom, audio-recorded, transcribed, and verified by an independent review team for quality control. The lead author sought clarifications from the participants through WhatsApp exchanges.

Table 1: Study participants

Method	JERO	AFIRD
3IDIs	1 (male)	2 (1 male, 1 female)
2 FGDs	1 FGD (4 male, 1 female)	1 FGD (3 male, 2 male)
1 SGI, merged	1 (male)	2 (1 male, 1 female)

Data analysis followed a case study analysis approach. Using a pre-determined coding framework derived from the research questions and Resilience Theory (Folke *et al.*, 2010), transcripts and field notes were deductively coded into three categories: climate resilience, community engagement, and navigating challenges. Each case was analysed independently

(within-case analysis) to produce detailed institutional narratives, then compared across cases (cross-case analysis) through a comparative matrix (Table 2). This revealed both shared patterns and distinct emphases. Manual qualitative data analysis integrated illustrative quotations to preserve participants' voices and contextual depth

Table 2: comparative matrix

Parameter	AFIRD	JERO Farm
Institutional focus	Formal NGO with national partnerships and structured programming.	Small, family -owned micro -farm with community roots.
Coverage	Works across multiple districts with formal programs in schools, prisons, and communities.	Operates on ~0.5 acre but influences via 120+ extension farms, 80+ women’s groups, and 50+ outlets.
Institutional engagement	Engages directly with district -level governance (e.g., Mpigi district demo garden)	Focused more on household and community advocacy

Visual analysis of three photos further enriched the findings. Following Shaari (2013), images were examined through pre-iconographic description, contextual analysis, iconographic interpretation, and iconological reading. Cross-image comparison tested typicality and refined interpretations, situating visual evidence within broader narratives of innovation, participation, and resilience. Written and verbal consent was obtained from study participants (Richard, Justine and Faizo), participation was voluntary, and confidentiality was maintained. Triangulation across methods enhanced credibility, while peer debriefing, Zoom team discussions, and member checking with key study participants (Justine, Faizo, Richard) ensured trustworthiness.

Interpretation of key findings

JERO Farm and AFIRD both champion urban agroecology in Uganda, but through distinct approaches. JERO emphasizes creativity, low-cost practices, and grassroots engagement, while AFIRD pursues structured, technically advanced systems with stronger policy and institutional links. Both foster resilience, innovation, and community empowerment, yet their contrasting methods highlight the adaptability of urban agroecology across diverse urban and peri-urban contexts. This study presents valuable insights into how urban agroecology can be tailored and mainstreamed in rapidly urbanizing Uganda. After analysing the data from the JERO farm and AFIRD study participants, the research team identified the following three themes (Table 2).

Table 2: Themes

Theme	Core focus	Key findings
Theme 1: Urban agroecology innovations for climate resilience	Ecological and technological innovations in space constrained urban settings	JERO Farm demonstrates small-space diversification, drip irrigation, hydroponics, composting, waste reuse, and closed- loop systems that stabilise production under climate variability. AFIRD integrates agroforestry, bio-input production, composting, and seed multiplication to support both adaptation and mitigation.
Theme 2: Community engagement in agroecological urbanism	Participation, learning, and social empowerment	JERO Farm uses free training, follow-up mentoring, school programmes, and women's groups to embed agroecology in daily life. AFIRD applies decentralised training, farmer-led learning centres, youth and women enterprises, digital platforms, and institutional engagement to scale learning across communities.

Theme 3:
Addressing urban
agroecology
challenges

Structural, institutional,
and market barriers

Key constraints include land scarcity and insecure tenure, costly and limited water access, weak policy recognition, low consumer awareness, high input costs, and fragmented markets. These barriers limit long term investment, scaling, and institutionalization of agroecology.

Theme 1: Urban agroecology innovations for climate resilience

Urban agroecology in the Kampala metropolitan area illustrates how small-scale, resource-constrained food systems respond to climate variability through adaptive and ecologically grounded practices. JERO Farm and the AFIRD Centre emerge as adaptive systems that integrate climate adaptation and mitigation within everyday urban food production. Their innovations demonstrate how resilience is built through diversity, recycling, reduced external inputs, and strengthened ecological feedback in dense urban environments.

At JERO Farm, water conservation and efficient resource use form the foundation of climate adaptation. The adoption of drip irrigation linked to hydroponic systems represents a response to increasingly unreliable rainfall and extended dry periods. As the team leader, Richard explained, "JERO [Farm] is actively making use of drip irrigation systems already." In urban and peri urban areas where piped water infrastructure is poorly developed, irrigation becomes unavoidable, yet water availability remains limited. Hydroponic systems that recycle water and nutrients, therefore, play a critical role in reducing vulnerability to water scarcity while maintaining production stability. Unlike rural systems characterised by seasonal production cycles, urban markets require a continuous daily supply of fresh vegetables and fruits. The stable irrigation infrastructure at JERO Farm, illustrated by the hydroponic system in Fig. 2, functions as a key climate adaptation strategy that buffers

production against rainfall variability while sustaining urban food availability.

JERO Farm further demonstrates how diversification and circular resource use enhance both climate adaptation and mitigation within severe spatial constraints. Operating on approximately half an acre of sloping terrain, the farm supports nearly 40 plant types through intercropping, terracing, sack gardens, and vertical production systems (Fig. 1). As Richard noted, "We are innovating mobile gardens... people pay more for a water bottle turned into a garden." The integration of fruit trees (Fig. 1) such as mango, passion fruit, and banana with vegetables including kale, marigolds, tomatoes, nakati(or African eggplant or *Solanum aethiopicum*), and onions strengthens functional biodiversity, which improves tolerance to heat stress, pests, and rainfall extremes. Organic waste streams are tightly managed, with food scraps converted into black soldier fly larvae for poultry and fish feed, while livestock manure is used to produce biogas. The resulting slurry is returned to the soil as organic fertilizer, reducing reliance on synthetic inputs and associated emissions. These closed-loop practices contribute to climate mitigation by lowering emissions from waste and fertiliser use, while also enhancing soil organic matter and moisture retention, thereby strengthening adaptive capacity. The reuse of urban waste materials, visible across the farm landscape in Fig 1, further supports climate adaptation by reducing plastic blockage in drainage channels and lowering flood risk during heavy rainfall events. Fig. 1 is strong

visual evidence of JERO Farm's approach to urban agroecology, combining diversified planting with recycled materials, terracing, and careful pathing to manage water and space.



Fig 1. Urban agroecology technologies at JERO Farm

At the AFIRD Centre, climate resilience is framed explicitly as the integration of adaptation and mitigation strategies within urban agroecological systems. Composting, household waste recycling, and the use of local seeds were described as accessible practices that reduce dependence on expensive external inputs while lowering emissions associated with fertiliser production and transport. As one participant explained, "People use home kitchen waste to make compost, manure... and don't depend on the expensive fertilisers." Agroforestry plays a central role in AFIRD's approach to climate adaptation by moderating microclimates and reducing urban heat stress. Justine, an AFIRD staff member, explained, "We don't use ACs [Air Conditioners]. Instead, we rely



Fig 2. Hydroponic system at JERO Farm

on natural cooling systems, which are made possible by the agroforestry practices established on the ground... when you move from a hot environment outside and enter through AFIRD's gate, you immediately start to feel the coolness."

She further noted that "a single mature tree can provide a cooling effect equivalent to several air conditioners," highlighting how small-scale tree planting contributes simultaneously to climate adaptation through temperature regulation and to climate mitigation through carbon sequestration. These agroforestry-based innovations are illustrated in Fig 3, which shows integrated agro-technologies at the AFIRD Centre.



Fig 3: Agro technologies at the AFIRD Centre, Nkoowe, Wakiso district.

AFIRD also links waste management innovations directly to climate action through biofertilizer production and seedling multiplication. As Faizo, an AFIRD staff member, explained, "...our tech looks at two aspects - mitigation... we are not only reducing emissions from waste but also building carbon sinks with the humus that farmers use. We are increasing adaptation through increasing access to low cost organic and biofertilizers. We multiply seedlings to promote tree planting." These practices strengthen mitigation by reducing methane emissions from unmanaged organic waste and increasing carbon storage in soils and biomass, while also enhancing adaptation by improving farmer access to affordable inputs that stabilise yields under climate stress.

While the two hubs differ in scale and institutional orientation, with JERO emphasising household level and micro scale innovations and AFIRD focusing on training oriented and technical interventions, both demonstrate how agroecological principles translate into concrete climate outcomes. Each reduces vulnerability to water scarcity, lowers dependence on external synthetic inputs, and creates ecological buffers against urban heat, flooding, and rainfall variability. Their integration of traditional practices with accessible technologies exemplifies agroecological urbanism, embedding food production, climate adaptation, and mitigation within the urban fabric. Despite their institutional differences, with JERO operating as a family run micro farm and AFIRD functioning as an NGO led training centre, both serve

as learning hubs within Kampala's urban socio ecological system. They provide demonstration spaces and training opportunities that strengthen adaptive capacity, support mitigation efforts, and create livelihood opportunities for youth and women. Together, these cases highlight how urban agroecology can contribute meaningfully to climate resilient food systems while advancing mitigation goals, even under conditions of spatial constraint and increasing climatic uncertainty.

Theme 2: Community engagement in agroecological urbanism

Community engagement is central to agroecological transformation in urban Uganda, and both JERO Farm and AFIRD demonstrate how participatory approaches strengthen social capital, empower marginalised groups, and build climate resilient urban communities. Community engagement emerges not as an add-on activity but as a core mechanism through which agroecological knowledge is co-created, adapted, and sustained over time. In both cases, learning, experimentation, and collective action link ecological practices with social organisation, thereby reinforcing adaptive capacity in rapidly urbanising contexts.

At JERO Farm, community engagement begins with accessible and practice-based learning. The farm offers free training sessions that focus on hands on skills and immediate application at household level. As Richard explained, "We allowed coming and learning free of charge... We help them establish kitchen gardens." These training activities are reinforced through follow-up visits, which create feedback loops between trainers and participants. As one farmer supported by JERO Farm noted, "Farmers ought to implement what they're taught and trigger JERO Farm to make follow up visits." This iterative process strengthens learning, accountability, and adaptation, ensuring that agroecological practices are embedded within

everyday household food systems and adjusted to local constraints.

Youth engagement is a deliberate and strategic focus at JERO Farm, reflecting the HLPE principles of co-creation of knowledge and human and social values. Through partnerships with organisations such as Rural Community in Development, JERO delivers agroecology education in schools. Richard, the JERO farm leader, explained, "We are hired by an organization to cover about nine schools... telling them about how they can grow without these chemicals." He emphasised the urgency of targeting younger generations, stating, "The biggest gospel should now go to the young generation... encourage them, embrace them, and give them awareness that this is how things are done." These interventions respond to widening disconnections between urban youth and food production. Reflecting on one encounter, he recalled, "I went to one of the biggest schools... a student thought food came from the store market." Practical demonstrations and school gardens therefore, function as adaptive learning spaces that reconnect youth to food systems while building long term resilience through knowledge transmission.

Women's engagement at JERO Farm further illustrates how agroecological urbanism integrates social inclusion with climate resilience. Through groups such as Women of Hope, women are supported to adopt agroecological practices that improve household nutrition and income. As Richard noted, "Led by the co-manager of JERO, the 33 participants of 'Women of Hope'... collaborate with JERO[Farm] in implementing agricultural techniques to improve their family's nutrition and income." JERO Farm positions itself not only as a training site but also as a socially embedded enterprise. Richard described the farm as "an organic demonstration farm that seeks to address issues of malnutrition... and evidence of how proper farming techniques can support families and communities and become profitable." This integration

of livelihood generation with ecological practices strengthens social resilience and enhances households' capacity to cope with climate and economic shocks. At AFIRD, community engagement operates at a broader and more decentralised scale, reflecting a systems-oriented approach to agroecological transformation. Engagement extends beyond individual farmers to include schools, prisons, markets, and organised youth groups. As Faizo explained, "Our community is quite broad. We work with schools, prisons, and farmers... We organize Open Days for people to come and see the urban farming technologies we are doing." These open learning spaces align with the HLPE principle of knowledge co-creation and reinforce resilience by enabling cross-sector learning and experimentation within urban socio-ecological systems.

AFIRD further strengthens participation through collaborative innovation processes. Farmers engage directly in the development, testing, and refinement of biofertilizers and biopesticides, contributing to local knowledge co-creation. Digital tools also support engagement and knowledge exchange. Through the iKnowFarm App, AFIRD markets products and disseminates agroecological information. As Faizo explained, "We enrich the app with information on markets and agroecology practices... and get support from the community in terms of content development and feedback." These mechanisms enhance adaptive capacity by linking local practice with wider networks of information, markets, and learning.

Youth and women empowerment are central to AFIRD's engagement strategy and closely linked to resiliencebuilding through livelihood diversification. Faizo observed, "Some of the youths are now making their pesticides... using garlic and onions, and they are selling them too." Women are similarly supported to

develop value-added enterprises based on agroecological production. One staff member explained, "Women groups we train... do herbal soap, body lotions, organic pesticides and teas, using herbs they grow in sack gardens." These activities connect ecological knowledge with income generation, reducing vulnerability to climate and economic stress while addressing broader challenges related to unemployment, nutrition, and health. Replication and decentralisation are defining features of AFIRD's model and reflect resilience theory principles related to redundancy, modularity, and scaling out. Justine described how "a network of facilitators learns innovations and transform their landscapes by establishing their agroecology learning model centres." Some participants have transformed their own homes into learning hubs. She recounted the example of "an old lady called Katabaire Joy... she has now created a 'Joy Centre,' and she is currently building accommodations for participants." Through this approach, agroecological knowledge is embedded within communities rather than concentrated in a single site. AFIRD's work has contributed to the establishment of up to 30 school and community green spaces, integrating agroecology into daily urban life and strengthening collective resilience.

AFIRD also engages strategically with government institutions to influence governance and policy environments. A permaculture demonstration garden established at the Mpigi District local government headquarters serves both as a learning space and an advocacy platform. Justine emphasised its role, stating, "Through exposures... government officials, farmers, and visitors learn innovations on the ground and then replicate them." By situating agroecology within formal institutional spaces, AFIRD enhances visibility, legitimacy, and the potential for wider adoption, aligning with HLPE principles related to responsible

governance and supportive enabling environments. Taken together, JERO Farm and AFIRD illustrate complementary pathways of community engagement within agroecological urbanism. JERO emphasises farm-based training, mentorship, and school partnerships, with a strong focus on youth and women as future custodians of agroecology. AFIRD adopts a more formalised, network-based approach that connects farmers, women, and youth to enterprise development, digital platforms, and decentralised learning centres. Both cases demonstrate that urban agroecology functions not only as a set of farming practices but as a participatory process of education, empowerment, and resilience building within Uganda's rapidly urbanising socio-ecological systems.

Theme 3: Addressing urban agroecology challenges
While urban agroecology offers important pathways for sustainable food production, environmental regeneration, and climate adaptation, practitioners in Kampala metropolitan encounter persistent structural, institutional, and social barriers that constrain its wider adoption. These challenges reflect misalignments among ecological innovation, urban governance, infrastructure, and market systems. Experiences from JERO Farm and AFIRD illustrate how such constraints shape everyday practice and limit the scaling of agroecological urbanism in peri urban environments. Land scarcity and tenure insecurity emerged as a central challenge undermining long-term resilience. As one AFIRD participant observed, "In Uganda and especially Kampala, people are using containers, vertical farming, rooftop farming, balcony farming, because there is no land." Justine echoed this concern, stating simply, "Land is a problem... land is inadequate." Insecure tenure increases farmers' exposure to sudden displacement and discourages long term investments in soil health, agroforestry trees, and water infrastructure that are central to agroecological

resilience. Faizo described the situation starkly: "Urban farmers are losing land at a very high rate. There is a lot to be done on land rights." This instability weakens feedback between ecological stewardship and social benefit. Participants therefore argued for stronger integration of agroecology into urban planning through designated agricultural zones. Justine criticised existing greening initiatives for prioritising aesthetics over function, stating, "KCCA [Kampala Capital City Authority] is creating green spaces... but when you look at what is planted, they are not even beneficial. We need to be intentional, not just after green colour, but plants that serve other purposes, medicinal, indigenous, useful trees."

Access to water represents another major constraint with direct implications for climate adaptation. Many urban farmers rely on purchased water, which significantly increases production costs and limits crop choices. As Justine explained, "Someone tells you I now spend like 1000 UGX to buy [a 20-litter jerrican of] water... they start to think they need to buy water for other plants they don't value." This situation reduces adaptive flexibility, particularly during dry periods when water demand increases. Collective solutions were proposed to strengthen resilience at the community level. Justine suggested shared infrastructure such as rainwater harvesting and communal water access, stating, "If possible, we have some common water points... it can give opportunities for people to always get some water to take care of their gardens." Such approaches align with resilience theory by emphasising shared resources and collective action to buffer climate stress. Market-related challenges further limit the viability of urban agroecology. Price instability driven by political and market dynamics undermines income security. As Justine noted, "Prices often rise due to political factors and market dynamics." At the same time, low consumer awareness constrains demand for agroecological

products. Faizo observed, "Many people are not aware of agroecology products, mainly the consumers." Justine added, "People don't know the value of these [agroecological] products... they just see [them as] vegetables." Without differentiation from conventional produce, agroecological products are undervalued. As Justine lamented, "They are put in the same markets [with conventional products] ... people don't see the difference." Faizo further explained how this affects livelihoods, stating, "You produce your small quantities, and you want to sell it at a higher price... but someone will tell you, I can get it cheaper in the market." These dynamics weaken producers' economic resilience and discourage the wider adoption of urban agroecology. Both practitioners emphasised the need for organised, farmer-led markets and designated stalls that recognise the added ecological and social value of agroecological produce.

High input costs and limited access to agroecological inputs compound these challenges. Justine noted that "Some of these inputs are expensive... and not easy to get [in urban establishments]." Faizo elaborated, stating, "Limited access to most agroecology inputs... fertilizers, seed, pesticides... keeps the production small." Even where local input production exists, scale remains a constraint. As he explained, "Even we who are engaged in processing them, the production is still small, probably because the levels of technologies we use are still low." These limitations restrict productivity, consistency, and the ability of farmers to respond to climatic variability. Proposed solutions included expanding composting facilities, scaling up bio input production, and strengthening farmers' capacity in seed saving and local input manufacture, all of which align with HLPE principles of recycling, input reduction, and autonomy.

Additional barriers relate to urban infrastructure and cost structures. High transportation costs and expensive market stalls reduce profitability and access to consumers. As Justine explained, "The cost of hiring

stalls and transporting produce is too high." Without supportive infrastructure and coordinated market systems, agroecological markets remain fragmented, increasing vulnerability for small scale producers.

Urban agroecology in Kampala is constrained by land insecurity, limited and costly access to water, weak consumer awareness, high input costs, and unregulated market competition. Practitioners from JERO Farm and AFIRD consistently argued for stronger municipal collaboration, the integration of agroecology into urban planning frameworks, improved market structures, and targeted support measures such as designated agricultural zones, subsidies, and demonstration sites. Despite these challenges, both initiatives continue to function as nodes of resilience within the urban socio-ecological system. However, scaling their impact requires systemic interventions that move urban agroecology beyond isolated projects and position it as a recognised and supported pillar of sustainable and climate-resilient city development.

Discussion of key findings

This study underscores the growing significance of urban agroecology as a locally adaptable, socially embedded, and ecologically grounded pathway for strengthening sustainable food systems in Uganda. Drawing on the case studies of JERO Farm and AFIRD, the findings demonstrate how urban agroecological practices function as integrated socio-ecological systems that simultaneously address food security, climate adaptation, and community resilience. Innovations such as resource recycling, diversified production, reduced use of external inputs, and participatory learning align closely with the HLPE agroecology principles and with resilience theory, which emphasises diversity, feedback, and adaptive capacity in the face of disturbance. Within the framework of agroecological urbanism, these initiatives show how food production, waste

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management, and social organisation are re-integrated into urban spaces, contributing to both climate adaptation and mitigation while advancing food sovereignty and ecological justice (Peano *et al.*, 2020; Rudolph and Muchesa, 2024).

The findings illustrate how urban agroecology strengthens resilience. At JERO Farm, practices such as mobile gardens, composting, drip irrigation, and diversified cropping reflect key resilience attributes including diversity, modularity, and efficient resource use, which enhance the system's capacity to absorb climatic shocks while maintaining core functions. At AFIRD, broader systemic interventions such as vermicomposting, agroforestry, bio input production, and seed multiplication demonstrate redundancy and functional diversity, both of which are central to resilient systems (Folke *et al.*, 2010). These practices also align with multiple HLPE agroecology principles (Wezel *et al.*, 2020), including recycling, input reduction, diversity, synergies, and resilience, illustrating how ecological processes are deliberately harnessed to stabilise production under conditions of environmental uncertainty.

Across both cases, learning and adaptation emerge as dynamic processes rather than static outcomes. By linking ecological innovation with continuous community training, experimentation, and feedback, JERO Farm and AFIRD exemplify core socio-ecological processes of adaptive learning and self-organisation. These processes resonate with the HLPE principles of co-creation and sharing of knowledge, human and social values, and culture and food traditions (Wezel *et al.*, 2020). In resilience theory terms, such feedback loops enable systems to adjust practices in response to disturbance, reducing vulnerability while expanding the range of possible responses to climate variability. This capacity for learning is particularly important in urban contexts, where environmental, social, and economic conditions are rapidly changing.

Community engagement plays a central role in strengthening social resilience and expanding adaptive capacity. JERO Farm's engagement with schools and women's groups embeds agroecological knowledge within households and everyday routines, reinforcing intergenerational learning and local stewardship. This approach reflects HLPE principles related to equity, social inclusion, and responsible governance, by prioritising access to knowledge for youth and women who are often marginalised in urban food systems. AFIRD's decentralised model of farmer-led learning centres and youth-led enterprises further exemplifies the principle of co-creation of knowledge and supports resilience through distributed leadership and redundancy. As argued by Rudolph and Muchesa (2024), embedding agroecology within education systems and participatory governance arrangements can catalyse broader systemic change, a finding reinforced by empirical evidence from both cases.

The adaptive reuse of urban waste materials for food production, particularly evident in JERO Farm's bottle and tyre gardens, illustrates resilience through transformability. Transformability, a core concept in resilience theory, refers to the capacity to create fundamentally new system configurations when existing conditions become untenable. By repurposing waste materials and underutilised urban spaces into productive agroecological landscapes, urban farmers actively reconfigure urban metabolisms toward circularity and sustainability. These practices strongly align with the HLPE principles of recycling, circular and solidarity economy, and efficiency in resource use, while echoing global examples of creative urban reuse documented by Suau (2015).

Despite these strengths, the findings also reveal structural constraints that limit the scaling and institutionalisation of urban agroecology. Insecure land tenure, limited access to affordable water, weak policy frameworks, and fragmented markets constrain farmers' ability to invest in long term ecological

functions such as soil restoration, agroforestry, and water harvesting. From a resilience perspective, these constraints reduce both adaptive capacity and transformability by locking agroecological initiatives into precarious niches. Similar barriers have been observed elsewhere. In Brazil, James *et al.* (2023) highlight the importance of enabling environments, including public programmes and supportive institutions, for scaling agroecology. Likewise, Sokolowski *et al.* (2024) and Monkes and Easdale (2023) show how fragmented implementation and state neglect undermine agroecological coherence in Latin America. These parallels situate Uganda's challenges within broader global patterns of uneven institutional support and political marginalisation of agroecology. The concept of agroecological urbanism (Tornaghi and Dehaene, 2021) provides a useful lens for interpreting these findings, especially for Kampala, where urban planning continues to prioritise commercial greening over multifunctional food-producing landscapes. Several HLPE principles, including responsible governance, circular economy, and connectivity between producers and consumers, remain weakly institutionalised in Kampala's urban policy. As Nicol (2020) argues through the framework of scaling out, scaling up, and scaling deep, urban agroecology must move beyond isolated grassroots experiments to reshape governance norms, planning frameworks, and cultural values. AFIRD's permaculture garden at the Mpigi District headquarters illustrates a strategic effort to influence governance by embedding agroecology within institutional spaces, thereby strengthening legitimacy and creating opportunities for policy learning.

JERO Farm and AFIRD demonstrate adaptability through ecological diversity, learning, and social organisation, and transformability through their efforts to contest urban systems that marginalise food production and informal livelihoods. However, without

coordinated governance, supportive infrastructure, and enabling policies (Anderson *et al.*, 2019), their transformative potential remains spatially limited and socially uneven. As Robbins *et al.* (2019) remind us, these constraints are not merely technical but deeply political, reflecting broader struggles over land, resources, and power in urban environments. Strengthening urban agroecology, therefore, requires not only technical innovation but also institutional reform that aligns urban governance with the full spectrum of HLPE agroecology principles and the long-term objectives of climate resilience.

Conclusions and Recommendations

Urban agroecology in Uganda emerges from this study as both an expression of everyday resilience and a practical pathway toward more just and sustainable urban futures. The experiences of JERO Farm and AFIRD demonstrate how community-led agroecological practices integrate ecological stewardship, social empowerment, and economic innovation within dense urban environments. Through small-space farming, bio-input production, and grassroots education, these initiatives simultaneously address food insecurity, climate risk, and youth unemployment, illustrating the capacity of urban agroecology to respond to multiple, interconnected challenges.

The identified constraints reduce adaptive capacity and limit the ability of agroecological initiatives to move from isolated sites of innovation to stable and transformative components of urban food systems. The study highlights that realising the transformative promise of urban agroecology requires coordinated action across research, theory, practice, and policy. Strengthening the evidence base, advancing urban focused agroecological theory, supporting community-based hubs of learning and innovation, and embedding agroecology within urban planning and governance frameworks are all essential. Without such systemic

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alignment, urban agroecology risks remaining marginal despite its demonstrated contributions to climate resilience, livelihoods, and social justice. Urban policy frameworks should formally recognise agroecology as a multifunctional land use that contributes to food security, climate adaptation, and ecosystem services. Municipal authorities should integrate agroecology into urban and peri urban planning through designated agricultural zones, secure land tenure arrangements, and long-term access agreements that enable farmers to invest in soil, water, and tree-based systems. Water governance should prioritise shared infrastructure such as rainwater harvesting, communal water points, and incentives for water efficient technologies. Market policies should support differentiated agroecological produce through designated market spaces, reduced stall fees, and public procurement schemes that recognise ecological and social value. Practitioners should continue to prioritise diversified, low-input, and circular production systems that enhance ecological functions and reduce dependency on external inputs. Scaling should emphasise replication and decentralisation rather than standardisation, supporting household, school, and community-based agroecology hubs as learning spaces. Training programmes should foreground participatory methods, farmer led experimentation, and locally adapted technologies, particularly those that improve water efficiency and waste reuse. Strengthening local capacity for seed saving, composting, and bio input production will enhance autonomy and resilience at farm and community levels. Social movements, farmer organisations, and civil society groups have a critical role in advancing urban agroecology as a political and cultural project. Advocacy efforts should focus on land rights, food sovereignty, and the recognition of agroecology within urban governance agendas. Building alliances among farmers, youth, women's groups, environmental

organisations, and consumers can strengthen collective power and visibility. Education and awareness campaigns should highlight the multiple benefits of agroecological food, linking nutrition, climate action, and social justice. By situating agroecology within broader struggles for equitable and sustainable cities, social movements can help transform urban food systems from the margins to the mainstream.

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Restoring resilience using holistic land and livestock management in semi-arid communal farming lands:Case studyof Dembe Stream catchment in Zimbabwe

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Abstract

Degraded rangelands and croplands, declining soil fertility, and reduced biodiversity are common challenges in Zimbabwe's semi-arid communal farming areas. These are primarily driven by unsustainable land and livestock management practices. Holistic land and livestock management (HLLM) is an agroecological approach that reverses ecosystemdegradation andbuilds community resilience to climate change. However, little empirical research has been conducted to evaluate the contribution of HLLM towards community resilience. This study, therefore assesses the impact of HLLM on ecological restoration in Ward 10 of Chinyika communal lands in Gutu District of Masvingo Province, Zimbabwe. Since 2019, communities were mobilised by a non-governmental organisation, Participatory Ecological Land Use Management (PELUM),to implement HLLM practices, including the use of mobile night bomas or moving kraals. The aim of adopting HLLM was to improve soil fertility, restore biodiversity, and enhance water retention and availability, particularly in the Dembe Stream catchment and surrounding villages. Using a mixed methods approach, data were gathered through interviews with community members, direct field observations, and participatory assessments of soil fertility, biodiversity, and hydrological changes. Information from community elders highlighted that the Dembe Stream stopped flowing during dry seasons from 1996 to August 2023. However, records from the Meteorological Services

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Department of Zimbabwe show no significant increase in precipitation in the area. Results indicate that following the adoption of HLLM in 2019 and its implementation in December 2020, dry season flows resumed in September 2023, thus restoring the stream's perennial status. HLLM significantly improved soil health, livelihoods, stream flow, social capital,resurgence of biodiversity, ecosystem services, and resilience. The study concludes that HLLM can effectively restore degraded ecosystems, enhance catchment water availability, support land productivity, and empower communities to sustainably manage their natural resources. This study contributes to the body of knowledge on the importance of using group or ultra-high density grazing towards environmental protection and improving livelihoods and ecosystem functionsand services in dry communal farming regions.

Keywords: agroecology, bomas, climate change, holistic planned grazing, Chinyika communal lands.

Résumé

La dégradation des pâturages et des terres cultivées, la baisse de la fertilité des sols et la réduction de la biodiversité constituent des défis communs aux zones agricoles communautaires semi-arides du Zimbabwe. Ces problèmes sont principalement dus à des pratiques de gestion des terres et du bétail non durables. La gestion holistique des terres et du bétail (GHTB) est une approche agroécologique conçue pour inverser la dégradation des écosystèmes et renforcer la résilience des communautés face aux changements climatiques. Cependant, peu de recherches empiriques ont été menées pour évaluer la contribution de la GHTB à la résilience communautaire. Cette étude évalue donc l'impact de la GHTB sur la restauration écologique dans le quartier 10 des terres communautaires de Chinyika, dans le district de Gutu, province de Masvingo, au Zimbabwe. Depuis 2019, les communautés ont été mobilisées par une organisation non gouvernementale, Participatory Ecological Land Use Management (PELUM), pour mettre en œuvre des pratiques de GHTB, notamment l'utilisation de bomas mobiles nocturnes ou d'enclos mobiles. L'objectif de l'adoption de la GHTB était d'améliorer la fertilité des sols, de restaurer la biodiversité et d'améliorer la rétention et la disponibilité de l'eau, en particulier dans le bassin versant du ruisseau Dembe et les villages environnants. Les données ont été recueillies par le biais d'entretiens avec les membres de la communauté, d'observations directes sur le terrain et d'évaluations participatives de la fertilité des sols, de la biodiversité et des changements hydrologiques. Les anciens de la communauté ont indiqué que le ruisseau Dembe s'était asséché pendant la saison sèche de 1996 à août 2023. Or, les relevés du Département des services météorologiques du Zimbabwe ne montrent aucune augmentation significative des précipitations dans la région. Les résultats indiquent qu'après l'adoption du modèle de gestion durable des pâturages (HLLM) en 2019 et sa mise en œuvre en décembre 2020, le débit de la saison sèche a repris en septembre 2023, restaurant ainsi le caractère permanent du ruisseau. Le HLLM a considérablement amélioré la santé des sols, les moyens de subsistance, le débit du ruisseau, le capital social, la biodiversité, les services écosystémiques et la résilience. L'étude conclut que le HLLM peut restaurer efficacement les écosystèmes dégradés, accroître la disponibilité en eau des bassins versants, soutenir la productivité des terres et permettre aux communautés de gérer durablement leurs ressources naturelles. Cette étude contribue à la connaissance de l'importance du pâturage en groupe ou à très haute densité pour la protection de l'environnement, l'amélioration des moyens de subsistance et le maintien des fonctions et services écosystémiques dans les régions agricoles communautaires arides.

Mots-clés: agroécologie, bomas, changement climatique, pâturageholistiqueplanifié, terrescommunautaires de Chinyika.

1. Introduction

Almost half of the world's habitable land is used for agriculture, and about a third of the population's livelihoods rely directly on it (Li *et al.*, 2025). Agricultural systems are constantly being improved to adapt to changing food tastes, environmental conditions, ensure food security, and support the livelihoods of growing populations. Resilient farming communities have the capacity to withstand and recover from shocks and stresses, such as global climate change, market fluctuations, local disruptions in livelihoods, ecosystem health, culture, supply of food, deteriorating soil quality, pests, and diseases. While Africa's collective contribution to greenhouse gas (GHG) emissions is less than 5 %, its economic, social, political, and environmental sectors are disproportionately affected by climate change (Fonjong *et al.*, 2024). The continent is highly dependent on climate-sensitive sectors like rainfed agriculture, experiences lots of conflicts, has weak socio-economic development, and low adaptive capacity to frequent natural disasters. Farming systems serve as sources and sinks of greenhouse gases (GHGs). They are critical in climate change mitigation, adaptation, and resilience. Agriculture serves as the second-highest GHG-emitting sector after energy, accounting for 11.7% of global emissions (Sokal and Kachel, 2025). In Zimbabwe, agriculture is also the second largest contributor to GHG emissions after the energy sector. The two sectors produce 45.9% and 37.1% of total GHG emissions in the country, respectively (Sithole *et al.*, 2023). Major emitters in this sector include livestock farming and agricultural soils, for example, the emission of methane from manure. Agriculture also contributes to GHG emissions through activities such as land-use change, energy use, deforestation, livestock production, nitrogen fertilizer use, and irrigation. The toolbox of solutions for addressing agricultural risks involves innovations to improve production,

social and economic capacities, strengthen resource management, and build resilience. Some approaches are in the early stages of piloting or are applied at local scales because expertise is maintained by traditional and indigenous knowledge systems (Sokal and Kachel, 2025). Whereas other strategies have been tried and tested, upscaled, and replicated. Climate-smart agriculture (CSA) practices, encompassing both nature and technology-based actions, offer promising solutions to improve productivity and mitigate GHG emissions (Sithole *et al.*, 2023).

1.1 Holistic land and livestock management

Holistic land and livestock management (HLLM) is an innovative framework restoring degraded land by employing mobile overnight kraaling and planned grazing (ACHM, 1992; Messner *et al.*, 2025). The use of mobile night kraals or bomas involves keeping cattle overnight in temporary movable kraals placed directly in crop fields. The purpose of night bomas is to deposit livestock excreta, concentrating nutrients and organic matter to naturally fertilise fields, hence improve soil fertility for crops (Nordborg, 2016). This reduces the need for manual labour to transport manure and increases crop yields, resource management, rangeland health, and sustainable livelihoods. Holistic planned grazing is a key rangeland management practice for land restoration and preventing overgrazing in paddocks. It harnesses the power of its hooves to break down hard ground so that air and water can penetrate. Livestock are kept at the right place, at the right time, with the right behaviour (Nordborg, 2016; Messner *et al.*, 2025). As livestock graze, defecate, stomp, and salivate, they build soil and deepen plant roots. Animal dung and urine help fertilize the soil loosened by hooves (ACHM, 1992; Huruba *et al.*, 2022). Farmers develop grazing plans for animals spend specific periods in a paddock before they are moved to another one. Scheduled or timed grazing in paddocks allows adequate time for plants to recover,

regenerate, keeps perennial grasses healthy, minimises the need to burn and expose soil. Short-duration overnight cattle kraaling in natural rangelands creates nutrient hotspots attractive to large mammalian herbivores (Huruba *et al.*, 2022). Nevertheless, very few studies have been conducted to determine the importance of holistic land and livestock management as an approach to building resilience in agriculture. This study explores the importance of HLLM in enhancing climate-resilient and sustainable food production in communal areas. Findings help to equip farming communities with practical strategies to strengthen climate-resilient agriculture and learn from real-world success stories. Chinyika communal lands in Zimbabwe were taken as a case study.

2. Materials and methods

2.1 Location and description of study area
Chinyika communal lands lie in a semi-arid region in the southeastern part of Zimbabwe. The main livelihood activity is subsistence crop and livestock production. Farmers grow maize as a staple crop, as well as sorghum, groundnuts, and millet. They also keep cattle, goats, donkeys, sheep, and poultry (Chirinda, 2024). Figure 1 shows the location of DhembeStream in ward 10 of Chinyika communal lands.

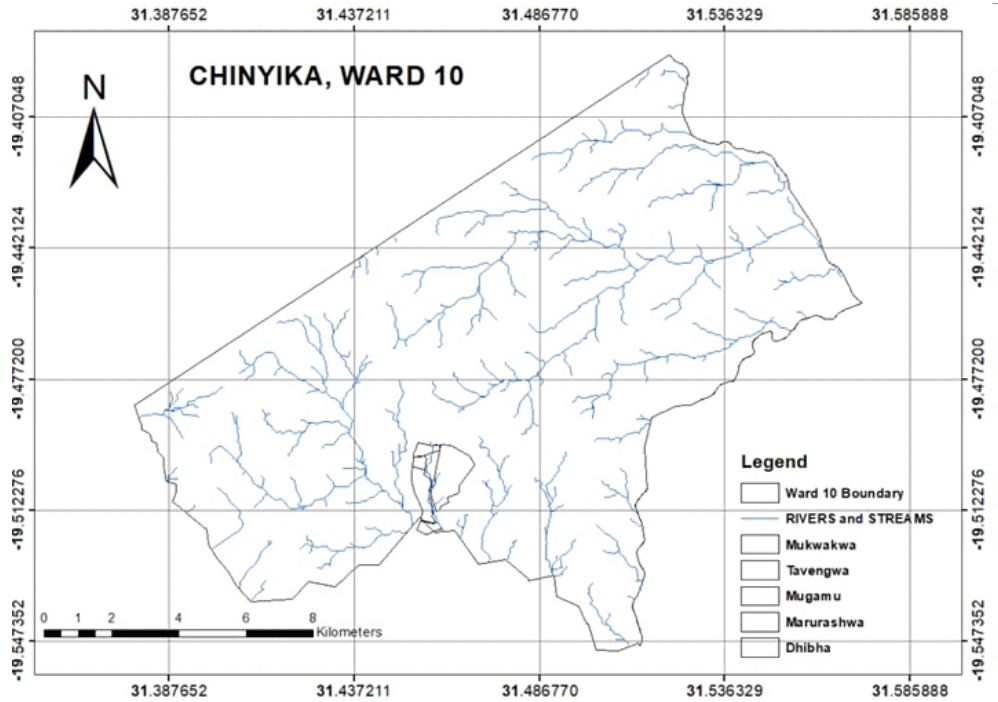


Figure 1. Layout of DhembeStream catchment and the 5 paddocks

The mean annual rainfall is 370.76 mm. The wettest month was 1990 while the driest month was 2008. The annual rainfall data series show a slight increasing trend from 1990 to 2023 (Figure 2)

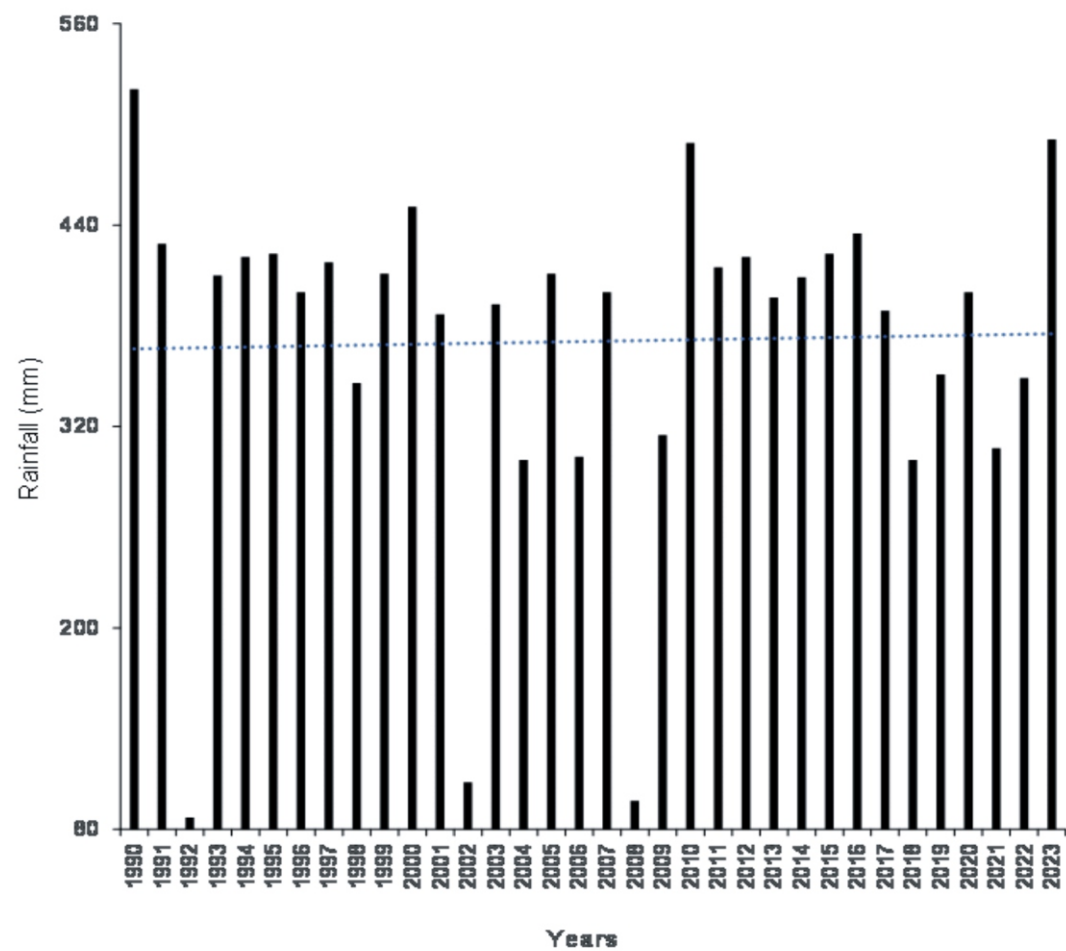


Figure 2: Variation of annual rainfall from 1990 to 2023

2.2 Social Mobilisation Process

Successful implementation of holistic management of land and livestock in Dembe Stream catchment evolved out of trust relationships and a long history of capacity building and strategic support (Table 1).

Table 1. Timeline of social mobilisation towards the agroecology movement

Timeline	Activity
1990s	Chinyika villagers experienced poor yields due to persistent droughts , hence they relied heavily on food aid and remittances.
1990’s-2018	Lack of resilience to droughts or poor rains experienced in the 1990’s was attributed to growing small grains, particularly finger millet,andmaize. Revitalisation of small grains movement using the guiding principle: ‘Food and economic self-sufficiency’encouraged each family to hold enough finger millet in storage to cater for 3 years.
2018	A small-grains field day was held. A HLLM expert was invited to attend the event, and relationships were initiated.
2019	The first gathering of the PELUM landscapes regeneration joint learning programme was initiated at the Seed and Food Festival in Harare. A 5-day workshop was held focusing on community mobilization, HLLM, including holistic planned grazing and principles of learning.

2020	First implementation of overnight mobile boma in crop fields during the dry season. First wet season when collective action herding was implemented.
2022	More than 80 cattle from 10 owners were used for night kraaling.The boma was moved to different croplands. Implementation of herding during the day continued in the dry season for 2 consecutive years from 2022.
September 2023	The Dembe Stream started flowing again during the dry season.
July & September 2024	Increase in implementation ofthe wet season grazing plan.
2025	Collapse of implementation of planned grazing during the dry season due to a lack of adequate enforcement to protect boundaries of paddocks.

Source: Survey results

2.3 Collection andAnalysis of Soil Samples

Soil samples were collected from a 0-15 cm depth of the soil profile. At this depth, there is the highest concentration of nutrients essential for plant growth. The sampleswere transported in sealed plastic bags and delivered to a laboratory at Fambidzanai Permaculture Centre in Harare for analysis. Soil samples were analysed for pH, organic matter content, and macronutrients including nitrogen (N), phosphorus (P), and potassium (K). Soil pH is an important determinant of nutrient availability, whereas organic matter is vital for soil structure and fertility. The analyses provided

baseline data on soil fertility, which is essential for agricultural planning and sustainable land management. The soil data were further subjected to principal component analysis (PCA). Percentage differences in soil properties were determined in holistic planned rangelands and crop fields, and their respective control or unimpacted lands.

2.3 Vegetation Assessment

We employed rapid and participatory methods of data collection, utilising the step point method to collect plant species across the rangelands(Evans & Love,

1957; Mentis, 1981). This is a quick method to determine field conditions. It shows significant merit for long-termvegetation monitoring (Oudtshoorn, 2014). However, the method has been criticised for a lack of accuracy (Biko'o *et al.*, 2025). Nevertheless, for participatory community-based monitoring, the method remains worthwhile. In this case, the method entails walking for 200 steps across an environmental gradient in the rangeland with a walking stick. After every two steps, the species or surface on which the tip of the walking stick landed is recorded. The ecological status of each identified plant species is also described, and relative frequencies are calculated to decipher species composition along the transect.

3. Results

3.1 Variation of grass species in areas under holistic planned grazing and open grazing

In areas under open grazing, five grass species were identified: *Hyparrhenia hirta*, *Eragrostis curvula*, *Eragrostis viscosa*, *Digitaria ciliaris*, and *Cynodon dactylon*. All these are classified as increasers, consistent with their tendency to dominate in overgrazed rangelands. Non-native species accounted for 6.5% of the recorded flora, including *Mimosa pudica*, *Chamaecrista nictitans*, *Digitaria ciliaris*, and *Asperula odorata*, collectively covering 36% of the transect. Although present, these species have not been declared invasive in Zimbabwe. Overall ground cover was classified as 28% grasses, 23% bare ground, and the remainder a mix of woody species, herbs, and forbs with limited grazing value.

In contrast, transects under holistic planned grazing supported eight grass species: *Hyparrhenia hirta*, *Eragrostis curvula*, *Melinis minutiflora*, *Melinis repens*, *Eragrostis viscosa*, *Eragrostis capillaris*, *Digitaria ciliaris*, *Heteropogon contortus*, and *Cynodon dactylon*. Grasses covered 39.6% of the transect, with all species classified as increasers except *Heteropogon contortus*, which is palatable when young. Bare ground accounted for only 7.5% of the transect. Non-native species, *Chamaecrista nictitans* and *Digitaria ciliaris*, contributed 17% cover. Notably, woody encroachers such as *Terminalia sericea* and *Dichrostachys cinerea* were also present along these transects.

3.2 Influence of Holistic Land and Livestock Management on Soil Fertility

HLLM had a positive effect on soil quality. Crop fields and rangelands under this system exhibit improved soil properties compared to unimpacted sites. In crop fields, pH values were 28% higher under holistic management. NPK, soil organic matter, and soil carbon were elevated by between 106% and 417.7% relative to controls. A similar trend was observed in rangelands: Soils under holistic management showed increases of 22% in pH, 58% in organic matter, 59% in soil organic carbon, 179% in phosphorus, 97% in nitrogen, and 121% in potassium compared to open grazing areas (Figure 3).

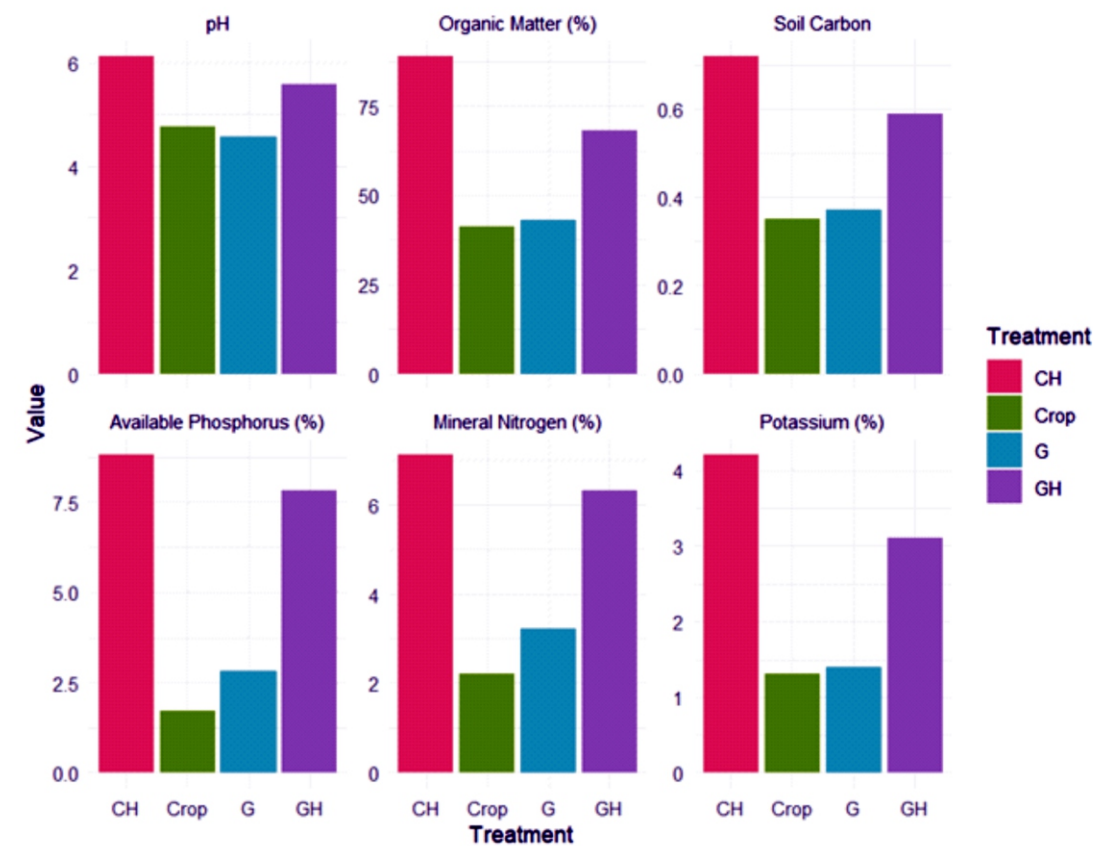


Figure 3. Comparison of selected soil variables on crop fields under holistic management (CH), crop fields with no holistic land management (Crop), and rangelands under holistic planned grazing (GH) and rangelands under open grazing (G)

The first PCA component explained 98.2% of the variation. All soil variables had relatively low loadings of about around 15%. The second PCA component explained 1.5% of variation. N (33%) and P (28%)

loaded highly on this component. The PCA biplot (Figure 4) clearly separated treatments, with the left side of the plot comprising open grazing and unimpacted crop fields having relatively lower values of soil variables. The right-hand side had relatively higher concentrations of soil parameters. Grazing under holistic management was largely associated with high N and P, while impacted crop fields were associated with high pH, K, soil carbon, and organic matter.

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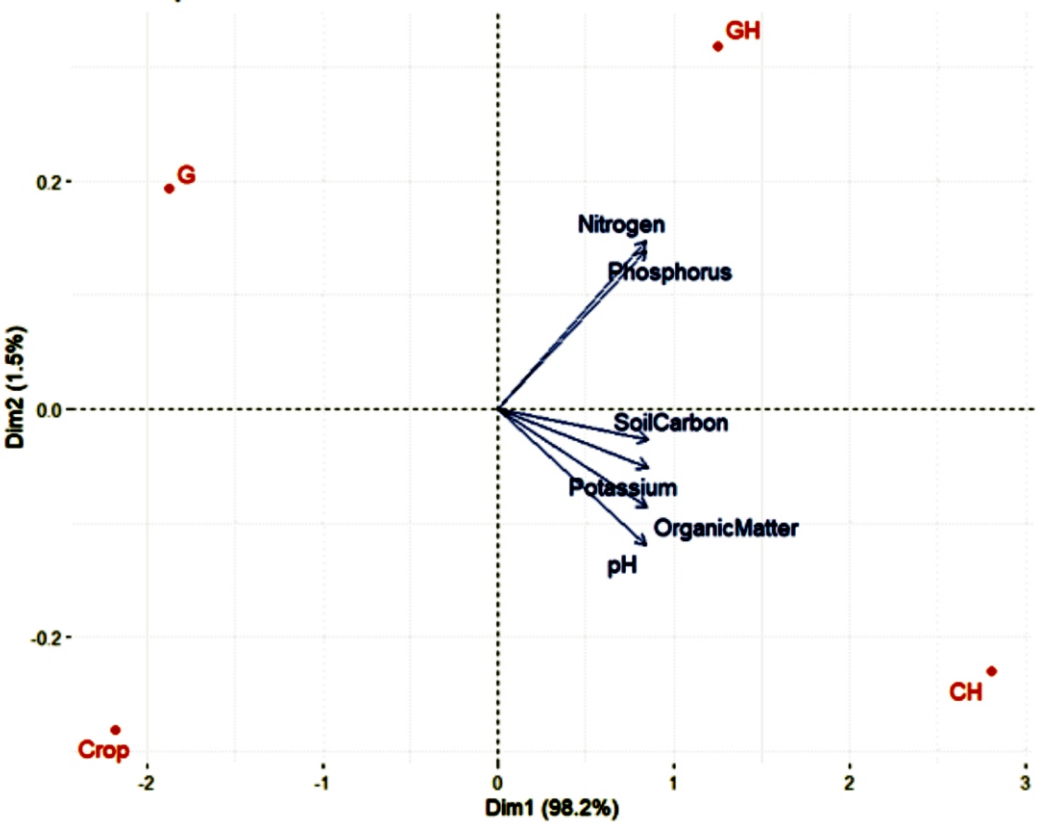


Figure 4: Impact of holistic land management on soil nutrients

3.3 Changes in Dembe Streamflows

Key informants indicated that prior to 1996 Dembe Stream flowed perennially into Chinyika River. There were abundant grass and enough water for watering animals and domestic use by riparian households. They also highlighted that during the 1996/1997 dry season; the stream was dry.

Community members observed that in September 2023, Dembe Stream started flowing for 500 m into the Chinyika River during the dry season. This occurred 2

years after implementating the grazing plan. Further upstream, there was a small puddle that remained with water until the end of April 2022. In 2020, the puddle was dry by end of March. In 2025, Dembe Stream continued flowing above ground all year. Since then, it is flooded during wet seasons.

4. Discussion

By implementing HLLM, farmers in Chinyika communal lands increased crop production and

improved animal management. They realised environmental benefits, including reduced land degradation in the paddocks. Soil nutrients also improved (Figure 4). Similar findings were reported by Huruba *et al.* (2022), where the community had experienced water problems, degraded land had developed hard surfaces, inadequate grass for livestock, declining crop yields. Livestock herders had to move 15 km to get water. They also camped at water sources for most of the dry season. However, HLLM rejuvenated dry streams, improved water availability, water infiltration, seed germination, animal health, and soil aeration. Most rivers in the area that had ceased to flow started flowing.

ACHM (1992) also observed that planned grazing and the use of bomas improved soil aeration and fertility, crop yields, rangeland management, and sustainable livelihoods. Land degradation was reduced, and pastures were improved in the dry semi-arid regions to the northwest of Zimbabwe.

5. Conclusion

This paper has shown that HLLM employs two approaches, namely, holistic planned grazing and mobile kraaling. The use of livestock regenerates the land, improves ecosystem function and health, and builds plant and wildlife biodiversity. The study highlighted that an increase in the plant density or grass

cover enhanced plant diversity, eradication and suppression of invasive species. Timed grazing restored grassland soils to their pristine state, inhibiting conditions that favour native species. This current work contributes to an emerging method of sustainable grazing by addressing some distinct knowledge gaps that link ecological and socio-economic systems.

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Authors' contributions

All co-authors contributed to the writing of this article.

Competing interests

The authors declare that he has no financial or personal relationships that may have inappropriately influenced them in writing this article.

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**IMPACT OF AGRICULTURAL TECHNOLOGIES IN STRENGTHENING
ORGANIC FARMING AMONG YOUTH FARMERS
IN SOUTHWESTERN NIGERIA**

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Abstract

This study examined the impact of agricultural technologies in strengthening organic farming among youth farmers in southwestern Nigeria. The study employed a descriptive survey design. A multi-stage sampling technique was employed to select 1,440 youth farmers who leveraged agricultural technologies from Ogun, Oyo, Ondo, and Ekiti States were purposively selected based on their predominance in organic food production. Data was analysed using descriptive statistics, t-test, and Probit regression. The results showed that most of the youth farmers were male (75.8%), married (83.5%), had an education (70.6%), had access to extension services (62.4%), technology usage (67.9%), and cooperative membership (85.4%). The t-test result showed a significant difference in the income of the youth farmers before and after the usage of agricultural technologies. Probit regression results revealed that technology usage ($\beta = 0.891$, $p < 0.01$), access to training ($\beta = 0.989$, $p < 0.01$), and farm size ($\beta = 1.724$, $p < 0.01$) significantly impacted organic food production in the study area. Conversely, the high cost of technology ($\beta = -1.621$, $p < 0.01$) and poor access to credit ($\beta = -1.392$, $p < 0.01$) remained barriers to adoption and usage of agricultural technologies. It is concluded that youth farmers with education, training, and credit facilities experienced higher income in the study area. The study, therefore, recommended that the usage of tractor-coupled implements, solar pumping machines, and access to credit facilities with supportive government policies may encourage massive youth participation in organic farming in southwestern Nigeria.

Keywords: Agricultural technologies, organic farming, youth farmers



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Résumé

Cette étude a examiné l'impact des technologies agricoles sur le renforcement de l'agriculture biologique chez les jeunes agriculteurs du sud-ouest du Nigéria. L'étude a utilisé une enquête descriptive. Un échantillonnage à plusieurs degrés a permis de sélectionner 1 440 jeunes agriculteurs des États d'Ogun, d'Oyo, d'Ondo et d'Ekiti, sélectionnés de manière ciblée en raison de leur prédominance dans la production d'aliments biologiques. Les données ont été analysées à l'aide de statistiques descriptives, du test t et d'une régression Probit. Les résultats ont montré que la plupart des jeunes agriculteurs étaient des hommes (75,8 %), mariés (83,5 %), instruits (70,6 %), avaient accès aux services de vulgarisation agricole (62,4 %), utilisaient des technologies (67,9 %) et étaient membres d'une coopérative (85,4 %). Le test t a révélé une différence significative dans les revenus des jeunes agriculteurs avant et après l'utilisation des technologies agricoles. Les résultats de la régression probit ont révélé que l'utilisation des technologies ($\beta = 0,891$, $p < 0,01$), l'accès à la formation ($\beta = 0,989$, $p < 0,01$) et la taille de l'exploitation ($\beta = 1,724$, $p < 0,01$) ont un impact significatif sur la production d'aliments biologiques dans la zone d'étude. À l'inverse, le coût élevé des technologies ($\beta = -1,621$, $p < 0,01$) et le faible accès au crédit ($\beta = -1,392$, $p < 0,01$) demeurent des freins à l'adoption et à l'utilisation des technologies agricoles. Il en ressort que les jeunes agriculteurs bénéficiant d'une éducation, d'une formation et d'un accès au crédit ont perçu des revenus plus élevés dans la zone d'étude. L'étude recommande donc que l'utilisation d'outils agricoles attelés aux tracteurs, de pompes solaires et l'accès au crédit, associés à des politiques gouvernementales favorables, puissent encourager une participation massive des jeunes à l'agriculture biologique dans le sud-ouest du Nigéria.

Mots-clés: technologies agricoles, agriculture biologique, jeunes agriculteurs

Introduction

Agricultural technology, also known as agtech or agritech, refers to the application of scientific and engineering principles to improve agricultural practices. It encompasses a broad range of tools, techniques, and innovations designed to enhance crop and livestock production, increase efficiency, and promote sustainability in farming (Afolabi and Osei, 2024). It includes the use of modern machinery such as tractors, combines, harvesters, and other equipment designed for efficient planting, harvesting, and processing of crops. It can also be a combination of precision farming technologies such as drones, GPS systems, sensors, and data analytics to optimize resource use (water, fertilizer, pesticides) and improve crop yields (Ogboru, 2025). It can be the use of information and communication technology (ICT) such as mobile devices, software, and cloud-based platforms for farm management, market access, and information sharing as well as renewable energy

technologies like implementing solar, wind, and other renewable energy sources to power farms and reduce reliance on fossil fuels to meet the growing global demand for food by optimizing yields and efficiency and minimizing water usage, reducing fertilizer and pesticide application, and promoting soil health as well as reducing costs, increasing productivity, and improving market access for farmers (Adeolu *et al.*, 2025). Digital technologies in agricultural production refer to the use of electronic devices, software, and networks to optimize farming practices, increase efficiency, and improve crop yield (Ghazi *et al.*, 2021). This includes tools such as drones, sensors, and smart farming applications that collect and analyse data to inform decision-making processes. The agricultural sector remains a central pillar of Nigeria's economy, employing nearly 70 % of the population and contributing 22.35 % to the country's Gross Domestic Product (GDP) in 2021 (Adeoti *et al.*, 2021). Agricultural technologies and digital tools,

including mobile applications, precision agriculture, and blockchain technology, have been recognized for their potential to transform agricultural practices, leading to improved yields, resource management, and market access to farmers all over the world, including in Southwestern Nigeria (Ogboru, 2025). These technologies can significantly reduce labour costs and improve efficiency. The integration of digital technologies in agriculture, as buttressed by Oluwasemilore and Oluwasola (2021) facilitates information dissemination, empowering farmers with timely data on weather conditions, pest management, and market prices. Furthermore, mobile apps have been developed to connect farmers to agronomists and experts, fostering knowledge exchange and improving farming techniques (Ihenacho *et al.*, 2021). Despite the sector's importance for economic growth, poverty reduction, and national food supply, food insecurity remains widespread and persistent (Ogunniyi *et al.*, 2022). The vulnerability of small holders is compounded by their dependence on rain-fed agriculture, poor access to inputs and credit, and weak post-harvest infrastructure (Eze *et al.*, 2021). Moreover, the lack of effective agricultural technologies and digital devices leads to lower food production and high post-harvest losses, reducing both farmer income and food availability (Adeolu *et al.*, 2025). The Ogun State, with its fertile soil and favourable climate, has immense potential for agricultural growth, but farmers in the region face numerous challenges, including limited access to information, inadequate financial services, poor market linkages, climate change, and low agricultural productivity, among others (Ogunniyi *et al.*, 2022). The low agricultural production in the region could be due to the current practice among farmers in the region. Most farmers rely heavily on traditional farming systems, which have impacted negatively on their farm output. This situation calls for targeted interventions that address the barriers to digital technology adoption

and embrace comprehensive approaches to enhance the effective utilisation of digital technologies by farmers in the region (Adeoti *et al.*, 2021). Understanding these imbalances between organic food production and rapid population growth will provide insights into how agricultural technologies can be leveraged to strengthen organic farming among youth farmers in southwestern Nigeria.

Methodology

The study was carried out in the southwestern geopolitical zone of Nigeria. The Southwestern zone lies between latitudes 50N and 90N, with an area of 114,271 square kilometres representing 12% of the country's total land mass. The zone has four distinct sub-ecologies, namely: swamp, mangrove forest, moist and dry lowland forest, and derived savannah. The zone comprises Oyo, Ogun, Osun, Ondo, Ekiti, and Lagos states (Adeoye and Ademolu, 2022; Ogun State Diary, 2025). A descriptive research design of survey type was adopted for this study in the form of a well-structured questionnaire, and oral interviews were used to elicit information from the respondents. The reliability of the instrument was determined using the Cronbach alpha reliability test, which yielded a reliability coefficient of 0.87%. A multi-stage sampling technique was used to select 1,440 youth farmers in organic farming. Data were analysed using descriptive statistics such as frequency counts; percentages, mean, and standard deviation were used to describe the socio-economic characteristics of respondents. A t-test was used to determine the differences in the organic output and income of the youth farmers before and after the usage of agricultural technologies. Probit Regression was used to determine the socio-economic parameters of the respondents. Model Specification: Probit regression equation: Socio-economic parameters on the impact of agricultural technologies in strengthening organic farming among youth farmers in the study area

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Types of organic farming			
Arable Crops	775	53.8	
Fruits/Vegetables	312	21.7	
Spices	353	24.5	
Farm size (hectares)			
<1 hectare	186	12.9	
1 – 2 hectares	310	21.5	
3 – 4 hectares	678	47.1	
> 4 hectares	266	18.5	
Sources of capital			
Personal savings	9	0.6	
Loan from Cooperative	1197	83.1	
Government grant	6	0.4	
Bank loan	3	0.2	
Group contribution (Esusu)	162	11.3	
Salary	63	4.4	
Seasonal output (Kg) Before			5,986
1,000 – 5,000	613	42.6	
5,001 – 10,000	559	38.8	
10,001 – 15,000	208	14.4	
15,001 and above	60	4.2	
Seasonal output (Kg) After		14,331	4,010
1,000 –5,000	102	7.1	
5,001 –10,000	300	20.8	
10,001– 15,000	608	42.2	
15,001 and above	430	29.9	
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Seasonal income (₦) Before		₦956,921.00	₦255,236.01
0–1, 000,000	945	65.7	
1, 000,001 – 1, 500,000	303	21.0	
1, 500,001 – 2, 000,000	190	13.2	
> 2, 000, 001	2	0.1	
Seasonal income (₦) After		₦1,911,340.22	₦594,710.22
0 – 1, 000,000	103	7.2	
1, 000,001 – 1, 500,000	318	22.1	
1, 500,001 – 2, 000,000	667	46.3	
> 2, 000, 001	352	24.4	
Membership of a cooperative			
Yes	1230	85.4	
No	210	14.6	
Access to extension services			
Yes	899	62.4	
No	541	37.6	
Access to free training			
Yes	1023	71.0	
No	417	29.0	
Number of technologies used		5	2
1 – 3 technologies	159	11.0	
4 – 6 technologies	603	41.9	
> 6 technologies	678	47.1	
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Source: Field Survey, 2025

Table 1 shows that the majority (75.8%) of the arable youth farmers were male, while 24.2% were female. This implies that both male and female youth farmers leveraged agricultural technologies to grow organic food in the study area. The majority (83.5%) were married, 70.6% had formal education, 53.8% were into arable farming, 83.1% sourced capital through loans from the cooperative, 85.4% were members of the cooperative, 62.4% had access to extension services, and 71.0% had access to free training, while 47.1% used more than 6 agricultural technologies on their farms. This aligns with the findings of Hashmiu et al. (2022), who found that married individuals often demonstrate increased responsibility towards adopting sustainable agricultural practices to secure family livelihoods. Cooperative membership and credit access play a pivotal role in promoting innovation adoption due to access to resources, training, and knowledge sharing in food production (Afolabi and Osei, 2024). The mean and standard deviations of respondents' age were 37.5±9.9 years, households size 5±2 people, farming experience 8±4 years, seasonal output before

the use of agricultural technologies 5,986±1,231kg and 14,331±4,010kg after the use of agricultural technologies, seasonal income before the use of agricultural technologies N956,921.00±N255,236.01, seasonal income after the use of agricultural technologies N1,911,340.22±N594,710.22 and number of technology used were 5±2 technologies respectively. Similar findings were reported by Akinrotimi *et al.* (2022), who emphasized that educational attainment, household size, and income significantly facilitate the uptake of innovative technologies by enhancing understanding, awareness, and practical implementation capacity. Previous studies, including those by Adeolu *et al.* (2025), highlight that farm size and access to credits can significantly impact the adoption of resource-intensive technologies due to scalability issues. This supports the findings of Akinrotimi *et al.* (2022), who reported that the adoption of digital devices in agricultural services significantly influences the marketability of perishable farm produce through sales platforms, online markets, and online orders.

Types of Agricultural Technologies used in organic farming

Table 2: Distribution of respondents on the types of agricultural technologies used

Technologies	Frequency	Percentage
Hardware Technologies		
Tractor-mounted implements	57	4.0
Disc plough and harrow	56	3.9
Nursery trays	227	15.8
Drip irrigation kits	160	11.1
Solar water pumping machines	103	7.2
Solar CCTV Cameras/bulbs	38	2.6
Digital weighing scale	250	17.4

Manure kits/trays	138	9.6
Greenhouses	100	6.9
Software Technologies		
e-Agroshops/marketing	30	2.1
e-Extension services/innovations	41	2.8
e-Updates on organic farming	43	3.0
e-Weather forecast updates	51	3.5
e-Banking apps	146	10.1

Source: Field survey, 2025 Note: Yes (1), No (0)

Table 2 clearly identifies the types of agricultural technologies adopted and used by youth farmers in organic farming in the study area were digital weighing scale (17.4%), nursery trays (15.8%), drip irrigation kits (11.1%), e-Banking apps (10.1%), manure kits/trays (9.6%), solar water pumping machines (7.2%), greenhouses (6.9%), tractor-coupled implements (4.0%), disc plough and harrow (3.9%), e-Weather forecast (3.5%), e-Updates on organic farming (3.0%), e-Extension services/innovations (2.8%) and solar cctv cameras/bulbs (2.6%) while e-

Agroshops/marketing (2.1%). This implies the respondents used one or two types of agricultural technologies for organic food production. These results support the findings of Adeyongo *et al.* (2022) on the adoption of agricultural innovations among farmers in the Federal Capital Territory, Nigeria. Adopting different types of agricultural technologies by farmers, like digital extension services, can provide farmers with instant access to agricultural advice, prices, and weather forecasts, which will ultimately enhance their agricultural production (Afolabi and Osei, 2024).

Impact of Agricultural Technologies on Organic Farming

Table 3: Table 3: Mean rating of the responses of respondents on the impact of agricultural technologies on organic farming among youth farmers in the study area

Items	Mean	SD
Technologies help to increase organic efficiency, productivity, and sustainability	4.0	1.1
Digital devices help in data-driven decision-making in organic farming	3.9	1.0
Blockchain technologies enhance the organic food supply and higher yields	3.8	1.0
Technologies increase farmers’ income and improve their livelihood	3.6	0.9
Technologies create employment opportunities for youths in organic farming	3.4	0.9
Technologies create market opportunities for organic produce and products	3.0	0.9
	2.8	0.8

They improve access to innovative market information through platforms	2.8	0.7
Mobile extension and advisory services are provided to farmers in rural areas	2.7	0.7
They connect buyers and sellers to reduce post -harvest losses of organic produce	2.6	0.7
They enable organic farmers to adopt climate-smart agricultural practices	2.6	0.7
Enhancing food supply chain transparency and traceability through blockchain	2.5	0.7
Leveraging AI and machine learning to predict pest outbreaks and controls	2.5	0.5
Offering virtual training programmes for farmers on the best organic practices	2.5	0.5
Creating online platforms for farmers to share knowledge and experiences	2.5	0.5
Using online markets to connect farmers with co nsumers and reduce middlemen	4.5	0.8
Digital soil mapping technologies to analyse soil health for better crop yield		
Grand mean		

Source: Field survey, 2025. Note: Strongly Agree (4), Agree (3), Disagree (2) and Strongly Disagree (1). Mean cut-off point = 2.5
Table 3 showed that the sixteen (16) items had means (x ?) that ranged from 2.15 to 3.99, which is above the cut-off point of 2.5, with youth farmers obtaining a grand mean of 4.45 and a standard deviation of 0.78. This implies that all the respondents were not far from the mean and from one another in their responses. These

results agree with the findings of Eze et al. (2021), who emphasized the role of blockchain technology in enhancing agricultural supply chains in Nigeria. These results corroborate the findings of Oyediran and Tijani (2021) on the role of digital technologies in promoting food and nutrition security in Nigeria. It is also in tune with the findings of Gupta and Rajput (2021) on mobile applications for farmers to access weather and market updates.

Challenges Limiting the Adoption and Usage of Agricultural Technologies in Organic Farming

Table 4: Mean Ranking of the responses of respondents on the challenges limiting the usage of agricultural technologies for strengthening organic farming in the study area

Challenges	Mean	SD	Rank
High cost of agricultural technologies	2.9	0.7	1 st
Poor access to credit facilities	2.9	0.7	2 nd
Resistant to change/adoption	2.9	0.6	3 rd
High cost of digital devices	2.8	0.6	4 th
Limited access to the internet for information	2.7	0.5	5 th
	2.6	0.5	6 th

Limited access to free trainings	2.5	0.5	7 th
Lack of technical know-how	1.9	0.5	8 th
Lack of equity for loans	1.8	0.4	9 th
Lack of awareness	1.7	0.4	10 th
Inadequate research support	1.6	0.4	11 th
Limited market access	1.6	0.4	12 th
Poor extension services	1.6	0.4	13 th
High cost of organic produce/products	1.6	0.3	14 th
Unstable electricity			

Source: Field survey, 2025. Note: Severe (2), Mild (1), and not a challenge (0) Mean = 1.5
Table 4 identifies substantial challenges limiting the adoption and usage of agricultural technologies for strengthening organic farming among youth farmers in the study area. High cost of technologies (1st), poor access to credit facilities (2nd), resistance to change/adoption (3rd), and high cost of digital devices (4th) were ranked as they emerged as major impediments. These findings agree with earlier studies of Johnson and Williams (2022), which emphasized that the financial burden of digital technologies in smallholder agriculture significantly hinders technology adoption and usage. Furthermore, limited

access to the internet for information (5th), limited access to training (6th), and lack of technical know-how (7th) are also notable challenges. These factors negatively impact the practical feasibility of adopting and using advanced agricultural technologies and leveraging digital solutions among arable youth farmers, as supported by recent findings from Ogboru (2025).

Testing of Hypotheses

Hypothesis One
There is no significant difference in the seasonal output of the youth farmers before and after the use of agricultural technologies in the study area.

Table 5: T-test Analysis on the seasonal output of the youth farmers before and after the usage of agricultural technologies in the study area

Variables	t value	p value	Decision
Organic output before	9.10	0.01	Significant
Organic output after			

Source: Field Survey, 2025 Significant at p<0.05
Results in Table 5 revealed that there is a significant difference in the seasonal output of the youth farmers before and after the usage of agricultural technologies in the study area (t = 9.10; p<0.05). This finding supports the findings of Eze and Okeke (2023) that the combination of agricultural technologies, indigenous knowledge, and community participation in the sustainable management of organic farming produce and products in southwestern Nigeria significantly contributed to their farm harvest.
Hypothesis Two
There is no significant difference in the seasonal income of the youth farmers before and after the usage of agricultural technologies in the study area.

Table 6: T-test Analysis on the seasonal income of the youth farmers before and after the usage of agricultural technologies in the study area

Variables	t value	p value	Decision
Seasonal income before	11.24	0.03	Significant
Seasonal income after			

Source: Field Survey, 2025 Significant at p<0.05
Results in Table 6 showed that there is a significant difference in the seasonal income of the youth farmers before and after the usage of agricultural technologies in the study area (t = 11.24; p<0.05). This finding agrees with the findings of Adebayo *et al.* (2024), who found that the adoption of agricultural technologies increases farmers' output and income in arable food production.

Table 7: Probit regression analysis on the impact of agricultural technologies for strengthening organic farming among youth farmers in the study area

Variables	Coefficient (β)	Std Error	Z Statistics	P-value
Age	0.514**	0.712	1.29	0.050
Sex	0.593**	0.363	1.60	0.050
Education	1.410***	0.954	1.41	0.001
Farm size (hectares)	1.724	0.621	2.78	0.012
Household size	1.216	0.978	1.05	0.020

Farming experience (years)	0.341	0.792	1.24	0.000
Seasonal income (after)	0.710***	0.694	1.02	0.001
Membership of a cooperative	1.121	0.651	1.72	0.010
Access to extension services	0.744	0.366	2.03	0.000
Seasonal output (after)	1.190***	0.389	3.06	0.001
Access to free training	0.989***	0.361	2.74	0.001
Number of technologies used	0.834***	0.227	3.67	0.001
Types of technologies used	0.891***	0.329	2.71	0.001
Cost of technology	-1.621***	0.167	-3.72	0.001
Access to credit	-1.392***	0.191	-2.37	0.001
Types of organic farming	1.620***	0.538	3.01	0.001
Constant	-2.994	0.839	-3.57	0.001
Log-likelihood	-49.93			
LR chi ² (16)	60.96			
Prob > chi ²	0.0000			
Number of observations	1440			
Pseudo R ²	0.640			
Correctly Predicted Cases (%)	90.7%			

Source: Field Survey, 2025 Significant at *1%, **5%**

The probit regression results (Table 7) clearly established that technology usage (β = 0.891, p < 0.01), education (β = 1.410, p < 0.01), farm size (β = 1.724, p < 0.01), access to free training (β = 0.989, p < 0.01), number of technologies used (β = 0. 834, p < 0.01), types of technologies used (β = 0.891, p < 0.01) and income (β = 0.710, p < 0.01) positively impacted the likelihood of agricultural technologies for strengthening organic farming among youth farmers in the study area. This finding corroborates the findings of Ogboru (2025), who discovered that farmers' socio-economic characteristics and extension agents can use digital technologies to enhance agricultural production in southwestern Nigeria. This finding also supports the

findings of Hashmiu et al. (2022), who concluded that cash crops and food security can be encouraged by massive arable production, which is achievable by promoting digital solutions and green agriculture in Ogun State. Afolabi and Osei (2024) found that predictive tools and smart farming technologies boost cassava production in Nigeria. The negative correlation between high cost of technology (β = -0.621, p < 0.01), poor access to credit (β = -1.392, p < 0.01) indicates barriers to usage of agricultural technologies, a phenomenon similarly reported by Ogunniyi et al. (2022). Conversely, age (β = 0.921, p < 0.05) and sex (β = 0.582, p < 0.05) significantly bolster adoption and usage of agricultural technologies, reinforcing the critical role age and gender play in supporting technological advancements, as found by Peterson and

James (2021). This aligns with observations by Eze et al. (2021), who highlight younger farmers' propensity towards innovation and technology adoption in organic food production. R2 was 0.64, which means that 64% level of the variation in the impact of agricultural technologies for strengthening organic farming among youth farmers in southwestern Nigeria.

Conclusion
This study concludes that leveraging agricultural technologies has positively impacted and strengthened organic farming among youth farmers in southwestern Nigeria. Youth farmers with education, access to free training, credit facilities, manageable household size, and access to agricultural technologies had increasing income and improved crop yields, while the high cost of technologies, poor access to credit, resistance to adoption/change, limited access to the internet, and lack of technical know-how remained major challenges.

Recommendations
Based on the findings, the study recommended the following:
1. Farmers leveraging on agricultural technologies like tractor-coupled implements, solar pumping machines, nursery trays, drip irrigation kits, manure kits/trays, and access to credit facilities with supportive government policies should be put in place to encourage massive youth participation in organic farming.

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Assessing knowledge, Attitudes, and practices of Poultry Producers and consumers for designing an agroecological certification system in Benin

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Abstract

The agroecological transition involves the adoption of sustainable and resilient practices that break with conventional methods, requiring a shift in values towards environmentally friendly agriculture that promotes biodiversity. This study aims to define organic certification criteria that meet the needs of poultry breeders and consumers in southern Benin, in a context where certification systems remain insufficiently developed to support this transition. Key barriers include institutional challenges such as the absence of locally adapted certification standards reflecting smallholder farming realities, weak regulatory frameworks, high certification costs, inadequate farmer training programs, a shortage of qualified local inspectors and certification bodies, and low awareness among producers and consumers about the benefits and requirements of agroecological certification. The study was conducted among 78 breeders selected through purposive sampling, and 100 consumers chosen using stratified and simple random method in six communes of Benin: Glazoué, Agbangnizou, Abomey, Abomey-Calavi, Ouidah, and Tori Bossito. Data collected via questionnaire on KoboToolbox were analyzed using descriptive statistics, chi-square tests, and analysis of variance. Knowledge, Attitude, Practice (KAP) analysis reveals complex dynamics. Producers exhibit basic certification knowledge (score 3.11) and a positive attitude (2.05), yet implementation remains a zero-practice score (score 0), mainly due to economic and technical constraints. Although consumer interest in certified products is increasing, a persistent gap between purchase intention and actual behavior, driven by high prices, limited availability, and information deficits. These findings highlight that the effectiveness of an agroecological certification system depends on adapting standards to local realities, strengthening producers' training in agroecological practices, and implementing supportive public policies to overcome economic and technical barriers.

Keywords: agroecological certification, poultry farming, sustainable transition.?

RÉSUMÉ

La transition agroécologique implique l'adoption de pratiques durables et résilientes qui rompent avec les méthodes conventionnelles, nécessitant une évolution des valeurs vers une agriculture respectueuse de l'environnement et favorisant la biodiversité. Cette étude vise à définir les critères de certification biologique répondant aux besoins des éleveurs et des consommateurs de produits avicoles du sud du Bénin, dans un contexte où les systèmes de certification restent insuffisamment développés pour accompagner cette transition. Parmi les principaux obstacles figurent des défis institutionnels tels que l'absence de normes de certification adaptées localement et reflétant les réalités des petites exploitations, des cadres réglementaires insuffisants, des coûts de certification élevés, des programmes de formation inadéquats pour les agriculteurs, une pénurie d'inspecteurs et d'organismes de certification locaux qualifiés, ainsi qu'une faible sensibilisation des producteurs et des consommateurs aux avantages et aux exigences de la certification agroécologique. L'étude a été menée auprès de 78 éleveurs sélectionnés par échantillonnage stratifié et simple dans six communes du Bénin : Glazoué, Agbangnizou, Abomey, Abomey-Calavi, Ouidah et Tori Bossito. Les données recueillies par questionnaire sur KoboToolbox ont été analysées à l'aide de statistiques descriptives, du test du X² et de l'analyse de variance. L'analyse des connaissances, attitudes et pratiques (CAP) révèle une dynamique complexe. Les producteurs possèdent des connaissances de base en matière de certification (score de 3,11) et une attitude positive (2,05), mais la mise en œuvre reste nulle (score de 0), principalement en raison de contraintes économiques et techniques. Certes, l'intérêt des consommateurs pour les produits certifiés est croissant ; cependant, un écart persiste entre l'intention d'achat et le comportement réel, attribué aux prix élevés, à la disponibilité limitée et au manque d'information. Ces résultats soulignent que l'efficacité d'un système de certification agroécologique nécessite l'adaptation des normes aux réalités locales, la formation des producteurs aux pratiques agroécologiques et la mise en œuvre de politiques publiques incitatives pour lever les obstacles économiques et techniques.

Mots-clés: certification agroécologique, élevage de volailles, transition durable.

Introduction

The livestock sector plays a central role in Benin's economy, contributing 13.7% to the national Gross Domestic Product (GDP) in 2022 (DSA, 2023). Beyond its considerable economic weight, this sector is essential for ensuring food security and constitutes a fundamental pillar of rural development. Specifically, livestock farming provides animal protein to a growing population while simultaneously generating income for millions of rural and peri-urban households. However, the significant environmental impacts of livestock farming—whether practiced extensively or intensively—have made a transition towards more sustainable production systems strategically necessary

for Benin. Over recent decades, livestock systems in the country have undergone profound structural changes, marked by progressive intensification aimed at meeting rising demand for animal products. Although this intensification has contributed to higher production and improved meat availability, it has unfortunately exacerbated environmental degradation. Consequently, accelerated deforestation in livestock zones, alarming erosion of local biodiversity (Djaouga *et al.*, 2021), and contamination of water and soil resources by livestock effluents and veterinary residues (Djagba *et al.*, 2019) have become increasingly evident. This growing tension between production imperatives and ecological preservation underscores

the urgent need to reassess currently dominant agricultural models and explore more sustainable alternatives.

In this context, agroecology emerges as a promising pathway to reconcile production with sustainability. Defined as a holistic approach that improves agricultural systems by harnessing natural processes while minimizing synthetic inputs (Wezel *et al.*, 2020; Tiftonell, 2020), agroecology provides both a conceptual and practical framework for economically viable and environmentally sound livestock production. Specifically, it builds on key ecological principles, including diversification of production systems, nutrient recycling, maximization of biological synergies, and valorization of local resources. Nevertheless, despite its strong potential, the development of an agroecological poultry sector in Benin remains severely constrained by a major structural gap: the absence of an organic certification system adapted to local realities and the specific characteristics of Beninese production systems. Indeed, as highlighted by Boko *et al.* (2015) and Pougoué *et al.* (2019), the available infrastructure, prevailing farming practices, and level of technical support provided to farmers remain far below international standards required for formal organic certification. Consequently, this lack of an appropriate certification system prevents commercial valorization of products derived from sustainable practices, undermines consumer confidence in agroecologically labeled products, and reveals a profound disconnect between producers' intentions and capacities on the one hand, and consumers' perceptions, expectations, and purchasing behaviors on the other. Therefore, this study seeks to contribute to establishing standards for a poultry certification system that is technically feasible, economically accessible, and culturally appropriate in the Beninese context. From a theoretical perspective, the analysis is anchored in two complementary conceptual frameworks. First, the functional typology

approach is employed to characterize the diversity of poultry farming systems by identifying homogeneous groups of farms that share similar features and practices. This approach moves beyond a monolithic view of farming by recognizing the plurality of technical trajectories and productive rationales. Second, the Knowledge, Attitude, Practice (KAP) model, widely used in behavioral change studies, serves as a framework for systematically assessing producers' and consumers' perceptions and behaviors regarding agroecological certification. This model assumes that knowledge influences attitudes, which in turn shape practices, while acknowledging that this relationship is not always linear and can be mediated by various contextual factors.

1. METHODOLOGY

A mixed-methods design was adopted (Creswell and Plano Clark, 2018) to capture the complexity of perceptions, attitudes, and practices of poultry stakeholders regarding agroecological certification. The study was conducted in three agricultural development poles in Benin (4, 5, and 7), covering central, southern, and southwestern departments. These zones were selected because they concentrate poultry farms, represent dynamic areas of agroecological transition, and display socio-ecological heterogeneity, making them broadly representative of national poultry production (Yin, 2018). Regarding sampling strategy, purposive sampling (Patton, 2015) was used for producers, identifying 78 individuals actively engaged in, or interested in, agroecological practices based on criteria including the use of local feed, reduced stocking density, limited synthetic inputs, and free-range management. For consumers, stratified random sampling yielded 100 respondents across six communes, stratified by location (urban, peri-urban, rural), education, and socio-professional category. Data collection was conducted through structured interviews using a pre-tested questionnaire

digitized via Kobo Collect, with trained enumerators collecting data following ethical standards. Producer data included inputs, housing type, flock composition, space per animal, and sanitary practices, along with knowledge, attitudes, and practices on certification, while consumer data addressed knowledge (labels, benefits), attitudes (willingness to pay), and behaviors (purchasing habits, barriers). For data analysis, descriptive statistics summarized socio-demographic profiles, practices, and perceptions, while Chi-square and ANOVA tested associations and group differences using STATA and SPSS. Furthermore, Knowledge, Attitude, and Practice (KAP) scores were constructed to assess certification knowledge, attitudes, and reported practices, with correlation analyses (Pearson's test) examining interrelationships. Finally, qualitative responses were coded thematically, and triangulation of qualitative and quantitative results enhanced validity.

2. RESULTS

3.1. Socio-demographic characteristics of respondents

The analysis of the socio-demographic characteristics of surveyed consumers reveals several significant trends that contribute to a better understanding of poultry product buyers' profiles in the study areas. Regarding gender distribution, results show that 66% of surveyed men regularly consume poultry products, compared to only 36% of women. This statistically significant difference highlights a marked trend: men are more frequent consumers of poultry products than women in the Beninese context. This disparity may be linked to socio-cultural factors, particularly the traditional role of men as main decision-makers in meat purchases, as well as differences in dietary preferences and consumption habits between genders. Educational level also emerges as a key determinant of poultry consumption. A majority of respondents (61%) hold a university degree, and this group reports the

highest consumption rates. Conversely, individuals without formal education or with only primary schooling consume poultry products less frequently. This positive correlation between education and consumption likely reflects several mechanisms: higher purchasing power, greater sensitivity to nutritional quality and food safety issues, and better knowledge of the benefits of animal protein. Furthermore, a Chi-square test reveals a statistically significant association (10% threshold) between education level and prior awareness of poultry product certification. This suggests that both exposure to information on certification and the ability to understand its implications are positively influenced by educational attainment - an important consideration for awareness and communication strategies. The literacy rate among surveyed consumers is high, reaching 87%, while the illiteracy rate remains relatively low at 9%. A minority (4%) report being able to read without having completed formal education, indicating some heterogeneity in literacy levels. From an ethnic perspective, the Fon and Lopka groups represent the largest proportions of respondents (28% and 27%, respectively), reflecting the demographic composition of the study areas and underscoring the importance of considering cultural specificities when designing promotion strategies for certified products.

3.2. Characterization of agroecological-oriented livestock systems

An in-depth analysis of breeding practices implemented by surveyed producers highlights distinctive features of agroecological-oriented systems, confirming the initial hypothesis of substantial diversity within the Beninese poultry sector. This diversity is expressed through technical and organizational dimensions that clearly differentiate agroecological systems from conventional intensive ones.

In terms of feeding, agroecological systems are characterized by higher feed consumption per bird, likely due to longer rearing periods and slower growth rates. Importantly, these systems rely almost exclusively on farm-compounded feed prepared from local raw materials (cereals, by-products, fodder), whereas conventional systems depend heavily on complete industrial feed or commercial concentrates. This feed autonomy both reduces reliance on external inputs and valorizes local resources, but also presents challenges for certification, as feed composition and nutritional quality vary considerably across farms. Regarding space management, agroecological systems operate at significantly lower stocking densities than conventional ones. Birds benefit from more space, reducing stress and fostering natural behaviors (scratching, dust bathing, perching) while improving sanitary conditions by lowering infectious pressure. Such practices align with the principles of agroecology and organic farming, which place animal welfare at the forefront. Sanitary management also differs. In the event of mortality, burial is the predominant method in agroecological systems, whereas conventional farms

may use incineration or external disposal services. Burial reflects an integrated waste management approach where carcasses are recycled into the soil-plant-animal system, consistent with the circularity principles of agroecology. Finally, housing structures also diverge. Agroecological systems favor free-range or semi-open buildings, contrasting with the closed, climate-controlled structures typical of intensive farms. These allow regular outdoor access, natural light, and expression of foraging behaviors, promoting animal welfare despite certain biosecurity challenges. Such practices align closely with international organic farming standards.

3.3. Knowledge, Attitude, and Practice of producers
The analysis of Knowledge, Attitude, and Practice (KAP) scores among poultry producers reveals a critical gap between declared intentions and actual implementation of agroecological certification. This "intention-action gap," widely documented in behavioral change literature, constitutes a major obstacle to certification uptake in the Beninese poultry sector.

Table 1: Producers' KAP analysis result

Dimension	Mean score	Minimum	Maximum	Std. dev.
Knowledge score	3.11	1	4	0.85
Attitude score	2.05	0	3	0.42
Practice score	0	0	0	0

The knowledge dimension reveals strong foundational awareness, with an average score of 3.11 ± 0.85 out of 4 points. This indicates that most farmers possess a substantive understanding of certification benefits and core requirements. The standard deviation of 0.85 suggests moderate variability, with scores ranging from 1 to 4. Producers scoring at the upper end of the scale demonstrated a comprehensive understanding of certification as a quality assurance mechanism, recognized its potential for market differentiation and premium pricing, and could articulate specific requirements such as restrictions on synthetic inputs, animal welfare standards, and traceability protocols. Those with lower scores possessed only basic awareness without detailed knowledge of practical implications. The attitude dimension reinforces positive dispositions, with a mean score of 2.05 ± 0.42 out of 3 points. Producers view certification as relevant, potentially advantageous for both individual farms and the broader sector, and aligned with sustainable agriculture values. The low standard deviation indicates considerable consensus, suggesting widely shared positive perceptions. Qualitative data reveal this favorable attitude stems from multiple perceived benefits: enhanced market access, product differentiation, alignment with environmental stewardship values, potential premium pricing, and contribution to consumer trust in local products. Critically, statistical analysis reveals a significant positive correlation between knowledge and attitude at the 1% threshold. This empirically confirms that greater knowledge fosters more positive attitudes toward certification. Producers with a deeper grasp of certification concepts consistently demonstrate more favorable evaluations of certification's relevance and desirability. This finding underscores the pivotal role of training and information dissemination in cultivating receptivity to certification processes. However, despite this favorable combination, the

practice dimension reveals complete implementation failure, with zero score for all respondents. This unanimous null score represents a stark disconnect between what producers know and believe versus what they actually do. Not a single producer has initiated certification steps despite expressed interest, pointing to powerful structural barriers preventing behavioral translation. Qualitative analysis identifies several interrelated obstacles. First, economic constraints dominate, particularly high upfront and recurring certification costs, including inspection fees, annual renewals, infrastructure adaptation costs, and potential transitional productivity losses. For smallholders with limited capital and thin margins, these represent prohibitive barriers without financial support mechanisms. Second, technical constraints compound economic challenges. Producers lack specialized support to navigate complex certification requirements. Reliance on farm-compounded feeds, while agroecologically sound, creates standardization challenges since composition varies across farms, complicating nutritional documentation required by certification protocols. Many producers also lack necessary record-keeping systems and traceability mechanisms. Third, weak organizational capacity limits collective certification strategies that could reduce individual costs. Absence of strong cooperatives prevents resource pooling and economies of scale. Fourth, market uncertainties discourage investment. Producers perceive unclear market channels, uncertain price premiums, and absent guaranteed offtake arrangements. Without assured market access, certification appears as a risky investment with uncertain returns. These barriers create a "lock-in" situation where favorable dispositions cannot overcome structural constraints. This highlights that agricultural behavioral change requires not merely knowledge and attitudes, but enabling conditions, including financial support,

technical assistance, organizational infrastructure, and functioning markets.

3.4 Knowledge, Attitude, and Practice of Consumers

While producers demonstrate a clear intention-action gap driven by structural barriers, the consumer

perspective reveals an equally paradoxical but fundamentally different dynamic that challenges assumptions about the relationship between knowledge and purchasing behavior regarding certified products.

Table 2: Consumers' KAP analysis result

Dimension	Mean score	Minimum	Maximum	Std. dev.
Knowledge score	2.81	2	4	0.48
Attitude score	1.00	0	2	0.40
Practice score	2.18	1	3	0.94

The average knowledge score of 2.81±0.48 out of 4 indicates moderate awareness. Consumers possess basic familiarity - recognizing certification's general quality assurance purpose - but lack a comprehensive understanding of specific standards or verification procedures. The narrow range (minimum 2, maximum 4) and small standard deviation indicate fairly homogeneous knowledge levels. Qualitative responses reveal moderate-knowledge consumers typically recognize labels and understand certification implies quality guarantees, but cannot explain specific required practices or verification methods. The attitude dimension shows a neutral to slightly positive disposition (1.00±0.40), notably more tepid than producers' enthusiasm. This lukewarm attitude may reflect limited personal experience with certified products, uncertainty about tangible benefits justifying price premiums, skepticism about certification credibility in weak regulatory contexts, or that certification is not salient relative to other purchase

criteria like price, freshness, or convenience. Interestingly, practice scores are relatively high (2.18±0.94), suggesting favorable purchasing behaviors despite moderate knowledge and neutral attitudes. The large standard deviation indicates substantial heterogeneity, with some actively seeking certified products while others rarely purchase them. This pattern could reflect social desirability bias, confusion between certification and other quality attributes, or genuine purchasing driven by factors beyond explicit attitudes. However, the most striking finding emerges from cross-tabulation analysis across knowledge levels. Among consumers with moderate knowledge (scores 2-3), attitudes and practices are remarkably favorable, with adherence reaching 100%. This suggests basic awareness creates a strong appeal, consistent with assumptions that information promotes adoption. Paradoxically, this enthusiasm collapses among consumers with deeper knowledge (score 4), where

support plummets to merely 8%, representing more than a tenfold decline. This precipitous drop suggests that deeper knowledge paradoxically functions as a deterrent rather than an enabler. Despite this non-linear relationship, overall KAP correlations remain positive and significant at 1% threshold across the full sample, confirming dimensions are interrelated though more complexly than linear models suggest. Several mechanisms may explain why deeper knowledge reduces support. First, comprehensive knowledge exposes certification system complexity-multiple competing labels, technical standards variations, and potential greenwashing-generating confusion or skepticism about genuine quality guarantees. Second, informed consumers become acutely aware of substantial price premiums, leading to cost-benefit calculations deeming premiums unjustified given budget constraints or perceived marginal improvements. Third, deeper knowledge reveals gaps in enforcement, limited inspection frequency, or insufficiently rigorous standards, eroding trust in certification as a credible quality signal. Fourth, highly knowledgeable consumers may develop alternative quality assessment strategies based on direct producer relationships or informal reputation systems, rendering formal certification redundant. This paradox carries profound implications for certification system design. Simply providing more information may backfire if it reveals complexity, undermining trust. An effective certification system must prioritize simplicity, transparency, and credibility. Labels must be comprehensible without extensive technical knowledge. Criteria must be clearly communicated and genuinely enforced. Pricing must balance quality with affordability. The certification system must build trust through transparent governance, rigorous verification, and accountability. Consumer expectations reinforce these conclusions. Respondents emphasize clear, accessible information

without overwhelming jargon, transparent labeling enabling quick product identification, and fair pricing reflecting quality without excluding price-sensitive consumers. These articulated needs align with the interpretation that complexity, opacity, and affordability barriers explain the paradoxical decline among knowledgeable consumers, underscoring the imperative for a user-friendly, accessible certification system alongside technical rigor.

DISCUSSION

The findings highlight both opportunities and significant constraints for implementing agroecological certification in poultry farming in Benin, revealing complex dynamics that warrant careful interpretation. First and foremost, the study reveals a high diversity of poultry production systems, with a clear and encouraging trend toward agroecological practices. The distinctions observed between systems-particularly in terms of feed autonomy, stocking density, and sanitary management-are consistent with the work of Honvou *et al.* (2022), which demonstrated the heterogeneity of livestock systems in Benin. More broadly, this transition toward more sustainable practices reflects the global movement described by Tittone (2020), who emphasizes the urgent need to move away from the intensive agriculture paradigm to build more resilient and ecologically sound systems. However, while this diversity represents a potential foundation for certification, it simultaneously poses challenges for standardization, a tension that must be carefully navigated. Turning to the producer perspective, a critical paradox emerges. Despite possessing favorable attitudes and solid foundational knowledge about certification, producers show no concrete implementation whatsoever (null practice score). This substantial gap between intention and action is largely explained by economic and technical constraints that create

insurmountable barriers to entry. Specifically, the observed reliance on farm-compounded feed illustrates both a strength and a significant challenge: on one hand, it valorizes local resources and reduces dependency on external inputs, aligning with agroecological principles; on the other hand, it complicates the standardization process, which is a key prerequisite for formal certification systems. Furthermore, the variability in feed composition across farms makes it difficult to establish uniform nutritional standards and quality benchmarks. These structural obstacles corroborate the findings of Boko *et al.* (2015) and Pougoué *et al.* (2019), who identified similar constraints-including inadequate infrastructure, insufficient technical support, and prohibitive certification costs-as major impediments to the development of organic poultry farming in Benin. Consequently, without targeted policy interventions and financial support mechanisms, the translation of positive attitudes into concrete practices remains highly unlikely.

On the consumer side, the results reveal an equally striking and counterintuitive paradox. While moderate knowledge strongly favors adherence to certified products, with adherence rates reaching 100%, more in-depth knowledge paradoxically reduces support sharply to a mere 8%. This unexpected phenomenon, which contradicts the common assumption that more information leads to greater adoption, is akin to the "intention-action gap" theorized by Marsden (2013). Several mechanisms may explain this reversal. First, deeper knowledge may reveal the complexity of certification systems, potentially creating skepticism about their reliability or relevance. Second, better-informed consumers may become more acutely aware of the price premium associated with certified products, leading to affordability concerns that override their initial enthusiasm. Third, increased knowledge may expose perceived gaps in the credibility or transparency of certification labels,

eroding trust. This finding aligns closely with Magrini *et al.*, (2019), who argue that information alone is insufficient to drive behavior change if not accompanied by tangible accessibility, affordable pricing, and institutional credibility. Therefore, certification systems must prioritize not only awareness-raising but also trust-building and economic accessibility to prevent knowledge from becoming a barrier rather than an enabler.

Finally, the collective results underscore the absolute necessity of designing a participatory, locally adapted, and context-specific certification system. The dramatic decline in consumer support when knowledge deepens underscores the critical importance of transparent, simple labeling that avoids technical jargon, alongside accessible pricing strategies that do not exclude middle- and lower-income consumers. Moreover, producers' need for technical training, financial support, and collective organization mechanisms must be addressed systemically. This holistic approach confirms the arguments advanced by Salliou and Barnaud (2017) and Duru *et al.* (2015), who advocate for integrated approaches that combine farmer capacity-building, consumer education, supportive public policies, and systemic changes in both production practices and societal values. In essence, certification cannot be reduced to a mere technical standard; it must function as a comprehensive development tool that simultaneously strengthens producer capacities, builds consumer trust through simplicity and transparency, and receives robust backing from enabling policies. Only under these conditions can certification serve as an effective lever for agroecological transition in Benin's poultry sector.

3. CONCLUSION

This study shows that while agroecology holds strong potential for transforming Benin's poultry sector, its adoption remains hindered by significant structural and economic barriers. Producers display good knowledge and favorable attitudes but lack the means to implement

certification, while consumers express interest yet are discouraged by complexity, price, and trust issues when more deeply informed. Certification alone cannot drive the transition; it must be participatory, adapted to local

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A Biostimulant as a Lever for Agroecological Intensification: Assessing Impacts on Maize (*Zea mays* L.) in Benin

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ABSTRACT

In Benin, maize production is threatened by soil degradation and heavy reliance on chemical fertilizers, and this study tested an indigenous arbuscular mycorrhizal fungi bio stimulant as a potential agroecological alternative. Working with 200 farmers in southern Benin, the research compared a bio-stimulant-based system with local practices using a before-and-after approach to track agronomic, economic, and social changes. Baseline data showed stagnant yields of 1.29 t/ha and low gross margins of XOF 66,440/ha despite widespread use of synthetic inputs. In contrast, the on-farm trials showed strong adoption and satisfaction, with maize yields on treated plots rising to 6.2 t/ha and farmer gross margins increasing nearly nine-fold to about XOF 587,000/ha. Farmers also used less chemical fertilizer, a reduction confirmed by extension agents, highlighting environmental benefits alongside productivity gains. Overall, the results showed that indigenous AMF bio stimulants are effective, economically attractive, and well accepted, offering a practical route to improve maize yields, farmer income, and soil health while supporting sustainable agricultural intensification and informing future policy and scaling efforts in Africa.

Keywords: Agroecology, Arbuscular Mycorrhizal Fungi (AMF), Biostimulant technology, Maize productivity

RÉSUMÉ

Au Bénin, la production de maïs est menacée par la dégradation des sols et une forte dépendance aux engraischimiques. Cette étude a testé un biostimulant à base de champignons mycorhiziens arbusculaires indigènes comme alternative agroécologique potentielle. Menée auprès de 200 agriculteurs auSud-Bénin, la recherche a comparé un système à base de biostimulant aux pratiques locales, selon une approche avant-après permettant d'évaluer les changements agronomiques, économiques et sociaux. Les données initiales ont révélé des rendements en grains de maïs autour de 1,29 t/ha et de faibles marges brutes de 66 440 XOF/ha, malgré l'utilisation généralisée d'intrants de synthèse. En revanche, les essais en milieu paysan ont démontré une forte adoption et une grande satisfaction : les rendements en grains de maïs sur les parcelles traitées avec le biostimulant à base de champignons mycorhiziens arbusculaires (CMA) indigènes ont atteint 6,2 t/ha et les marges brutes des agriculteurs ont été multipliées par neuf, pour atteindre environ 587 000 XOF/ha. Les agriculteurs ont également utilisé moins d'engrais chimiques, une réduction confirmée par les agents de vulgarisation, soulignant ainsi les bénéfices environnementaux en plus des gains de productivité. Globalement, les résultatsmontrentque les biostimulants à base de CMA indigènessontefficaces, économiquementintéressants et bien acceptés. Ils constituent une solution pratique pour améliorer les rendementsen grains du maïs, les revenus des agriculteurs et la santé des sols, tout ensoutenantune intensification agricole durable et enéclairant les politiques et les efforts de déploiementfutursen Afrique.

Mots-clés: Agroécologie, Champignons mycorhiziensarbusculaires (CMA), Technologie des biostimulants, Productivité du maïs

INTRODUCTION

In Benin, continuous population growth exerts significant pressure on the agricultural sector to meet rising food demands. Current agricultural systems are heavily dependent on the continuous application of mineral inputs, a practice that, while boosting short-term yields, leads to long-term degradation of soil health, diminished food quality, and negative impacts on atmospheric and hydric systems (Plenchette *et al.*, 2005; Yang *et al.*, 2004). This dependency ultimately results in declining crop productivity, making it increasingly difficult to meet the population's nutritional needs. The imperative for sustainable agriculture has therefore shifted focus towards solutions that reduce high-input systems while ensuring sufficient food production (Thonar *et al.*, 2017). Among these, technologies based on beneficial soil microorganisms have emerged as a key strategy to regenerate soil health and ensure long-term sustainability (Agbodjato *et al.*, 2016).

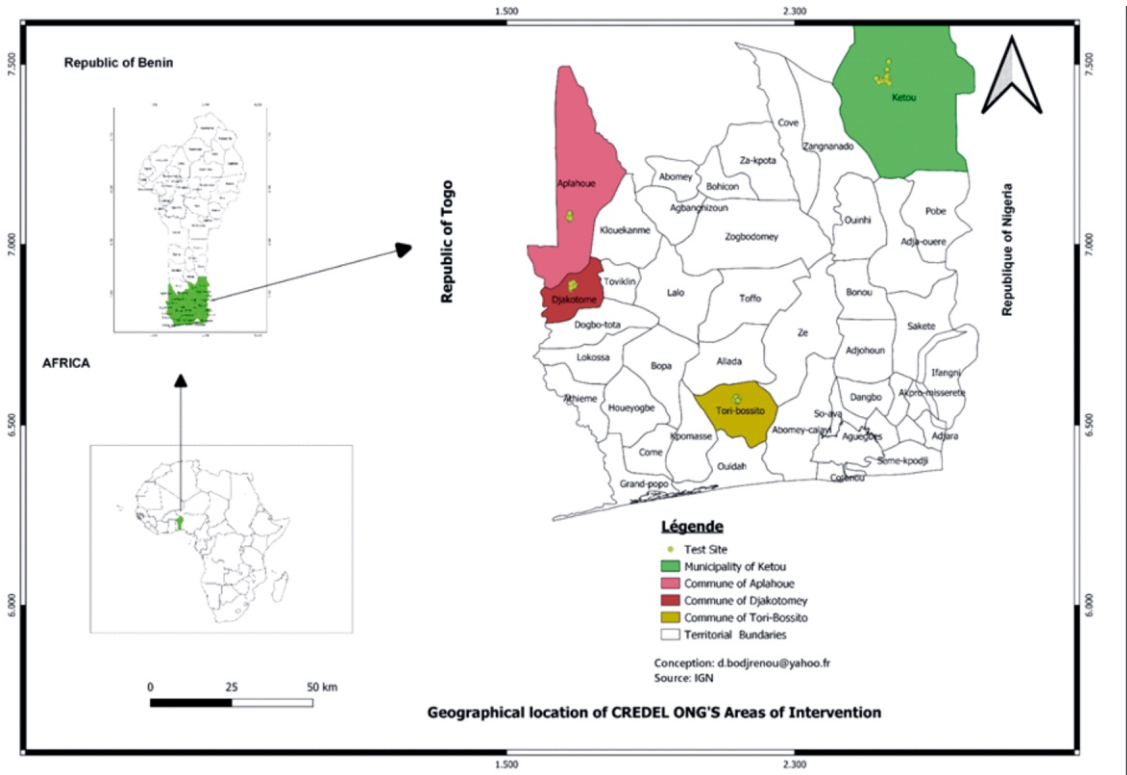
Maize (*Zea mays* L.) is a critical staple in Benin, essential for both domestic consumption and regional trade (N'Da *et al.*, 2014). Despite its importance, maize productivity is severely hampered by numerous constraints, chief among them being the constant decline in soil fertility due to land degradation (Saïdou *et al.*, 2012). As a modern and palliative solution to this challenge, the use ofbiostimulants based on indigenous arbuscular mycorrhizal fungi (AMF) offers a promising pathway. Numerous studies in Benin have already demonstrated the efficacy of this endomycorrhizal symbiosis in improving maize productivity (Akpode *et al.*, 2024; Alao *et al.*, 2024; Aguegue *et al.*, 2023, 2021, 2020; Assogba *et al.*, 2020; Koda *et al.*, 2020). The promotion and application of AMF-based bio stimulants are therefore expected to induce a sustainable improvement in maize yields, an increase in smallholder farmer incomes, and a progressive regeneration of soil microflora and fertility.

However, a critical knowledge gap remains regarding the performance, economic viability, and social acceptability of this technology under real-world, farmer-managed conditions. This study was therefore designed to bridge this gap., the main objective was to assess the real-world performance, economic viability, and social acceptability of the indigenous AMF bio stimulant under farmer-managed conditions.

MATERIALSAND METHODS

Study Area

The study was conducted at four Research-Development (R-D) sites: Eglimè, Zouzouvoun, Adakplamè, and Hayakpa. These sites were in the respective municipalities of Aplahoué, Djakotomey, Kétou, and Tori, belonging to the Departments of Couffo, Plateau, and Atlantique in Southern Benin (Figure 1). This region was chosen due to the predominance of maize cultivation and challenges related to declining soil fertility.



Data Collection

The study was conducted using a participatory on-farm approach under farmer-managed conditions. Two production systems were compared: the farmers' conventional maize production practices and a system integrating the indigenous AMF-based bio stimulant. The trials were implemented directly on farmers' fields, following locally relevant management practices, with technical support from agricultural extension agents. Data were collected on agronomic performance, input use, production costs, and farmer perceptions throughout the cropping season, forming the basis for agronomic, economic, and social analyses. A mixed-methods approach was used to collect data related to the study's objectives.

Agronomic Parameters

To assess crop growth and productivity, several parameters were measured. Plant height (using a measuring tape) and collar diameter (using a caliper) were recorded every 15 days, from 15 to 60 Days After Sowing (DAS). At 60 DAS, the leaf area of ten plants per plot was estimated using the formula: Leaf Area = Length × Width × 0.75 (Ruget and Chatier, 1996). At harvest (90 DAS), maize was collected, and grain mass was determined using a precision balance. The moisture content was measured with a moisture meter (LDS-1F), and the final grain yield (t/ha) was standardized to 14% moisture content according to the formula described by Ferro Valdés *et al.* (2013).

Economic and Social Parameters

To determine profitability, data on all production costs (labour, inputs) were collected in real-time throughout the season using individual data collection sheets. A partial budget analysis was then used to calculate the gross product value and the net agricultural income from each plot. Social acceptability and farmer perceptions were evaluated through structured surveys and interviews conducted at the end of the experimental period.

Data Analysis

The analysis followed a before-and-after (pre- vs. post-intervention) approach with a comparison group. First, a post-intervention descriptive analysis was conducted to profile the changes observed among beneficiary farmers using key variables such as yield, income, production costs, and perceptions of AMF. Means, standard deviations, and relative frequencies were used for comparisons. Second, a comparative before-and-after analysis was performed using paired Student's t-tests or Wilcoxon signed-rank tests (for non-normally distributed data) to evaluate significant variations in key indicators. Third, an analysis of adoption and perceptions was carried out, considering the AMF adoption rate and the number of trained users. Finally, a cost-benefit analysis was conducted to estimate the economic profitability of the technology by determining production costs, revenues, and gross/net margins. Data processing was performed using several tools: Microsoft Excel was used for basic calculations, pivot tables, and graphs. SPSS software was used for descriptive statistics, t-tests, and regressions. Qualitative data from semi-structured interviews and focus groups were analysed using NVivo software.

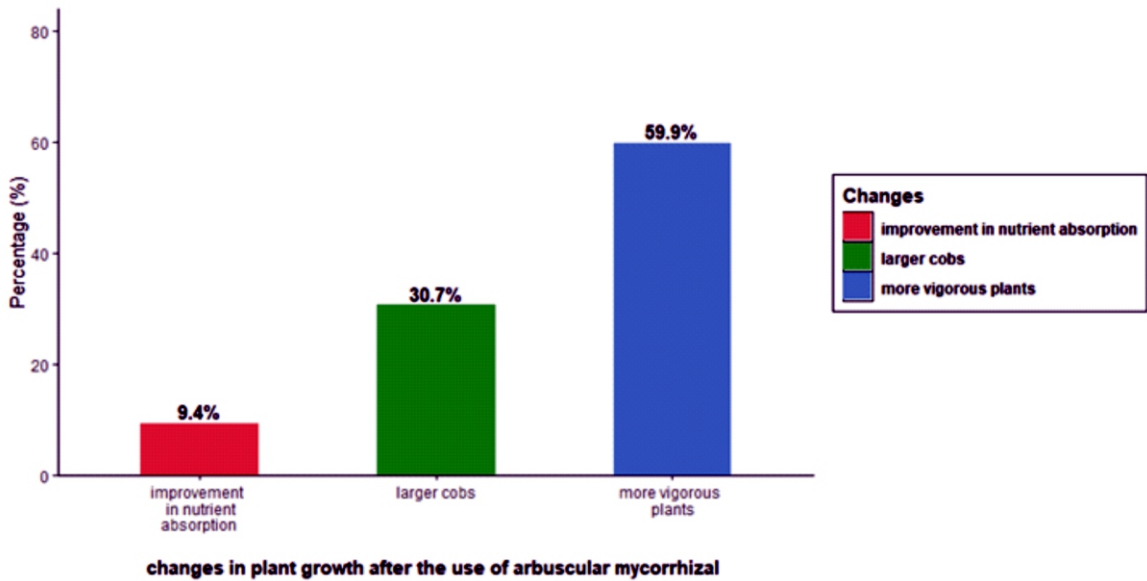
RESULTS

The results of the on-farm trials are presented below, structured according to the three primary research objectives. Baseline data from the initial reference study are compared with post-intervention data to quantify the impact of the AMF-based bio stimulant.

Agronomic Performance of the Bio stimulant Impact on Plant Growth and Farmer Perception

Following the application of the bio stimulant, farmers unanimously reported significant and visually apparent improvements in crop health and vigour on the treated plots. These qualitative observations were highly consistent across all study sites. Specifically, farmers

noted the development of more robust stems and denser, greener foliage compared to the control plots. When asked to identify the most significant changes, 59.9% of farmers primarily attributed the improvements to enhanced overall plant vigour, while 30.7% pointed specifically to the development of larger cobs, and 9.4% perceived an improvement in nutrient absorption (Figure 2). These perceptions collectively indicate that the bio stimulant induced a strong positive response in the vegetative and reproductive stages of the maize plants.



yield, confirming that the technology successfully translated enhanced plant growth into a substantial increase in grain production under real-world farming conditions.

Figure 2: Assessment of changes in plant growth after the use of *Arbuscular mycorrhizal fungi* (AMF)-based bio stimulants

Impact on maize grain yield

A dramatic increase in quantitative yield substantiated the positive agronomic perceptions. The on-farm trials demonstrated that the use of the bio-stimulant led to a highly significant improvement in maize productivity. The average grain yield on treated plots reached 6200 kg/ha, a stark contrast to the baseline average of 2743.4 kg/ha (Table 1). This represents more than a doubling of the

Table 1: Key Project Performance Indicators

Parameters	Before production	After production
Average quantity harvested (kg)	2,743.4	6,200
Average total costs of chemical fertilizers (NPK, Urea) (FCFA/ha)	67,831	58,750
Average total production costs (FCFA/ha)	174,947.91	122,500
Average total revenue (FCFA/ha)	463,465	709,725
Gross margin per ha (FCFA/ha)	66,440.104	587,225–

Impact on Production Costs and Revenue

The introduction of the AMF-based bio stimulant had a transformative effect on the economic parameters of maize production. The technology enabled a significant optimization of the cost structure. Average total production costs were reduced to XOF 122,500 per hectare, notably driven by a decrease in expenditure on chemical fertilizers, which fell to XOF 58,750 per hectare (Table 1). Concurrently, the substantial yield increase led to a dramatic rise in income. The average total revenue generated per hectare surged from a baseline of XOF 463,465 to XOF 709,725 post-intervention (Table 1). This demonstrates that the technology simultaneously reduced expenses while significantly boosting gross income.

Impact on farmer profitability

The combined effect of reduced production costs and increased revenue resulted in a dramatic improvement in farmer profitability. By calculating the difference between the new total revenue (XOF 709,725/ha) and the new total costs (XOF 122,500/ha), the average gross margin for farmers using the bio stimulant reached XOF 587,225 per hectare. This represents a nearly nine-fold increase compared to the baseline gross margin of XOF 66,440 per hectare. This substantial enhancement of profitability provided a powerful economic incentive for adoption and demonstrated the technology's capacity to significantly improve the livelihoods of smallholder maize farmers.

Social acceptability and farmer adoption

Following the on-farm trials, farmer perceptions shifted dramatically, indicating high social

acceptability. The technology was perceived as practical and easy to use, with 74.3% of farmers finding its application "easy" (Figure 3).

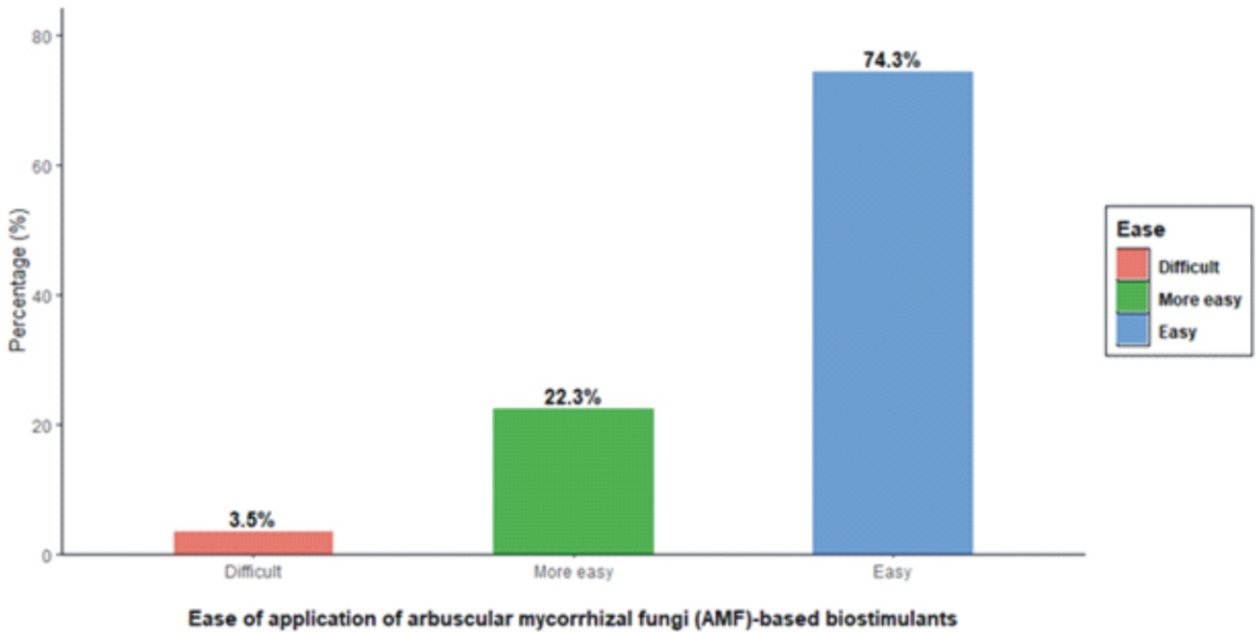


Figure 3: Evaluation of the ease of application of arbuscular mycorrhizal fungi (AMF)-based biostimulants. More importantly, the initial uncertainty regarding its effectiveness was overcome; an overwhelming

majority of 98% of farmers judged the bio stimulant to be either "useful" (63%) or "very useful" (35%) for their maize production (Figure 4).

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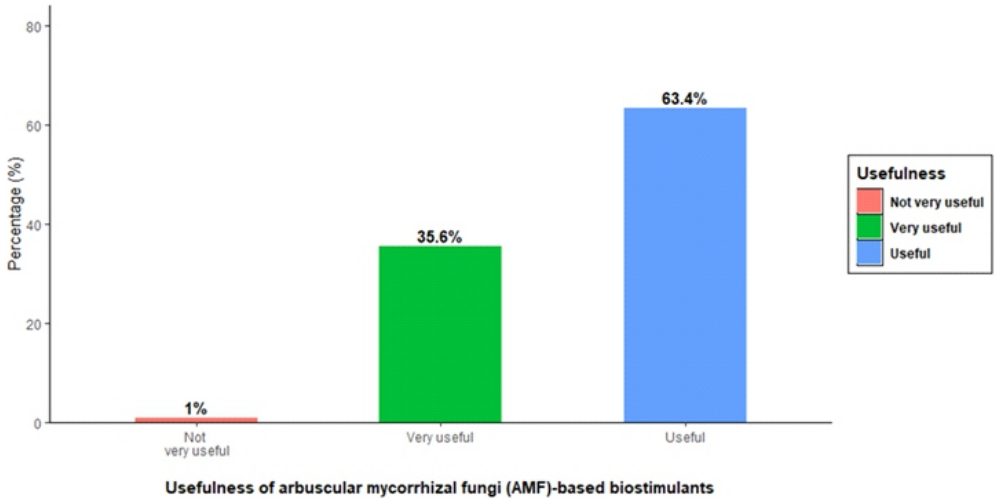


Figure 4: Assessment of the usefulness of arbuscular mycorrhizal fungi (AMF)-based biostimulants. This positive perception translated into an exceptionally high degree of overall satisfaction, with nearly 100% of participants reporting being either "satisfied" (approx. 70%) or "very satisfied" (approx. 30%) with the results obtained (Figures

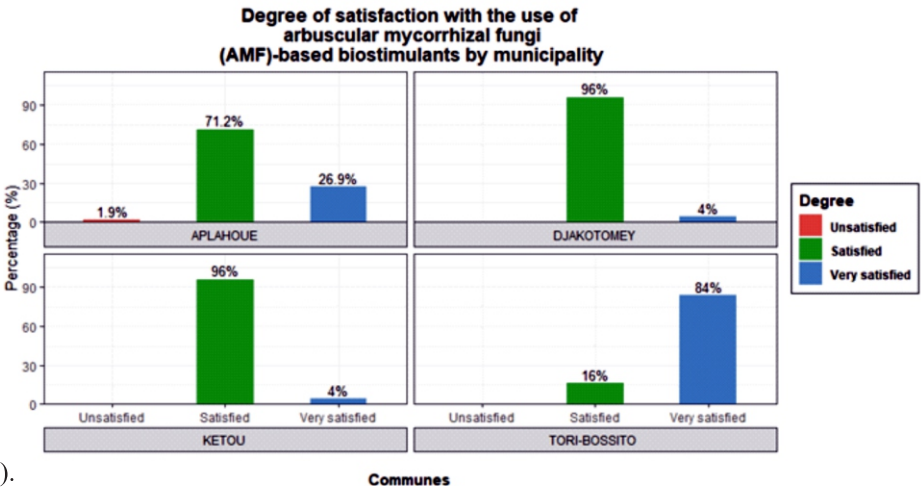


Figure 5: Degree of satisfaction with the use of arbuscular mycorrhizal fungi (AMF)-based bio stimulants by municipality

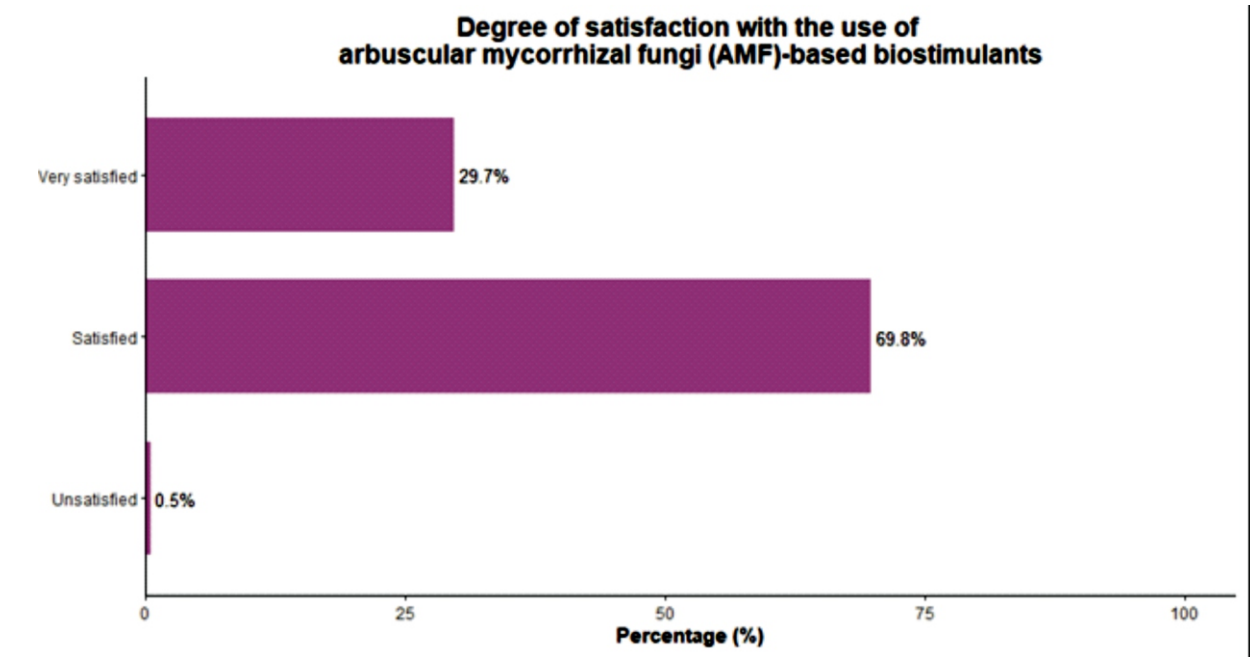


Figure 6: Degree of satisfaction with the use of arbuscular mycorrhizal fungi (AMF)-based bio stimulant

Drivers for future adoption

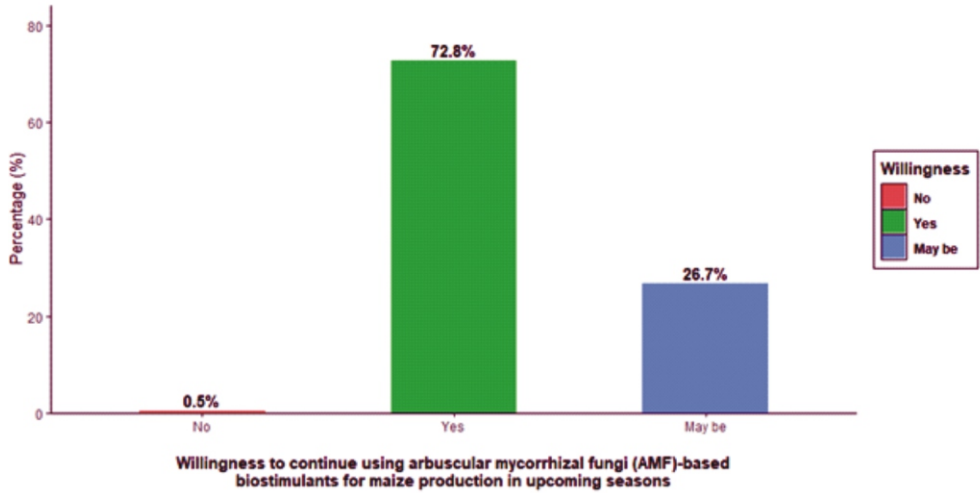
The high levels of satisfaction translated directly into strong indicators of future, long-term adoption. A

Figure 7:Willingness to continue using arbuscular mycorrhizal fungi (AMF)-based bio-stimulants for maize production in upcoming seasons.

This personal commitment was further reinforced by a strong willingness to act as advocates for the technology, with 67% of farmers stating they would recommend the AMF bio stimulant to other producers (Figure 10, Impact Study). Crucially, this perceived

significant majority of participants (72%) expressed a clear intention to continue using the bio stimulant for their maize production in the upcoming seasons (Figure 7).

value was quantified through a willingness-to-pay (WTP) analysis. The study found that farmers were prepared to make a financial



investment in the technology, with an average accepted price of XOF 1,649 for a 1 kg package and XOF 41,225 for a 25 kg bag (Tables 2 and 3). Taken together, these

behavioural intentions demonstrate that the technology is not only perceived as effective but is also considered a viable and desirable investment by smallholder farmers.

Table 2: Minimum and maximum purchase prices of arbuscular mycorrhizal fungi (AMF)-based bio stimulants per kilogram by producers

Price proposal	Aplahoué	Djakotomey	Kétou	Tori-Bossito	Overall
Average minimum purchase price of indigenous arbuscular mycorrhizal fungi (AMF)	1,540 (401)	1,668 (1,025)	1,816 (261)	188 (53)	1,305 (858)
Average maximum purchase price of indigenous arbuscular mycorrhizal fungi (AMF)	4,451 (884)	3,150 (1,270)	4,040 (493)	413 (529)	3,028 (1,789)

Table 3: Purchase formats of indigenous arbuscular mycorrhizal fungi (AMF) by producers Purchase format of indigenous arbuscular mycorrhizal fungi (AMF)

Purchase format of indigenous arbuscular mycorrhizal fungi (AMF)	Rank	Cost (FCFA)
Format 2: 1 kg bag	3rd	1,649
Format 1: 25 kg bag	1st	41,225
Format 3: 50 kg bag	2nd	82,450

DISCUSSION

This study successfully demonstrated that an indigenous AMF-based biostimulant can serve as a powerful lever for the agroecological intensification of maize systems in Benin. The on-farm results not only validate previous on-station findings but also prove the technology's effectiveness, economic viability, and social acceptability under the real-world conditions managed by smallholder farmers. The dramatic doubling of maize yield observed in the treated plots can be attributed to the well-documented mechanisms of the mycorrhizal symbiosis. AMF act as an extension of the plant's root system, vastly improving its capacity to explore the soil and absorb nutrients, particularly phosphorus, which is often a limiting factor in weathered tropical soils (Aguegue *et al.*, 2023; Smith and Read, 2008). The farmers' qualitative observations of more "robust stems" and "denser, greener foliage" are direct visual evidence of this enhanced nutrient uptake, which translates into greater biomass and, ultimately, higher grain yield. This confirms the crucial role of AMF as "ecosystem engineers" in improving soil health and plant nutrition (van der Heijden *et al.*, 2015).

From an economic standpoint, the nearly ninefold increase in gross margin is arguably the most powerful driver for adoption. This finding aligns with recent reports suggesting that bio stimulants can significantly enhance the economic resilience of smallholders (FAO, 2022). The high profitability provides a compelling "relative advantage," which, according to Rogers' Diffusion of Innovations theory, is a primary determinant of a new technology's adoption rate (Rogers, 2003). The technology also scored highly on other key attributes defined by Rogers: its application as a simple seed coating made it compatible with existing practices and low in complexity, while its rapid and visible effects ensured high observability. The exceptionally high rate of social acceptability and the strong intention for future use can be linked to this combination of perceived efficacy and ease of use. The participatory action-research approach, which included comprehensive training, was also instrumental in building farmer trust and capacity, overcoming the initial scepticism revealed in the baseline study. The success of this study is also coherent with findings from other parts of sub-Saharan Africa. For instance. Crucially, the use of indigenous

strains, as emphasized by Asghar *et al.* (2023), is a key factor in this success, as they are better adapted to local soil and climate conditions and avoid the ecological risks associated with introducing exotic microbial species. Despite these compelling results, the primary challenge for scaling remains the large-scale production and distribution of a quality-controlled, affordable inoculum. While this study confirms the demand and willingness-to-pay, establishing a sustainable supply chain will require a concerted effort involving public-private partnerships.

Conclusion

This research concluded that the indigenous AMF-based bio stimulant is a technically effective, economically viable, and socially accepted innovation for maize production in Southern-Benin. The study provides robust on-farm evidence that this technology can simultaneously achieve three critical goals: (i) the sustainable intensification of maize production through a significant increase in yields; (ii) the enhancement of system resilience through improved soil health; and (iii) a tangible increase in farmer income through both cost reduction and higher revenue. The large-scale adoption of this biological innovation could therefore play a key role in achieving Benin's national objectives for food security and sustainable agricultural development.

Recommendations

Based on these compelling results, the following actions are recommended to facilitate the transition from successful research to widespread impact:
1. Policy Support and Integration: Agricultural policymakers should formally recognize and integrate AMF-based biostimulants into national strategies for sustainable agriculture and soil health. This includes establishing a framework for quality control and certification to ensure farmers have access to effective, high-quality products.

2. Establishment of a Sustainable Supply Chain: A public-private partnership model should be developed to support the creation of local bio-production units. This would ensure a decentralized and reliable supply of quality-controlled, affordable inoculum to smallholder farmers.
3. Capacity Building and Extension: The national agricultural extension system (ATDA) should incorporate training modules on the benefits and proper application of biostimulants into its standard curriculum to ensure knowledge is disseminated effectively and to support farmer decision-making.

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EVALUATION OF BIOFERTILISER AS A SUSTAINABLE FERTILISER IN CROP PRODUCTION

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Abstract

Recent decades have witnessed increased crop production to match the global demand for food, feed, and pharmaceuticals by the increasing human population. Conventional agricultural practices are heavily reliant on artificial fertilisers that have numerous human and environmental health effects. In-view of this, sustainability/Agroecologist researchers and environmentalists have increased their focus on sustainable crop fertilization mechanisms. Biofertilisers are microbial formulations constituted of indigenous plant growth-promoting microbes (PGPM) that directly or indirectly promote plant growth through the fixation, solubilization, and mobilization of soil nutrients, and the production of plant growth-stimulating hormones and iron-sequestering metabolites called siderophores. Biofertilisers have continually been studied, recommended, and even successfully adopted to produce many crops in the world. These microbial products hold massive potential as sustainable crop production tools, especially in the wake of climate change that is partly fuelled by artificial fertilisers. Despite the growing interest in the technology, its full potential has not yet been achieved, and utilization still seems to be in its infancy. There is a need to shed light on the past, current, and prospects of biofertilisers to increase their understanding and utility. This review evaluates the history of PGPR biofertilisers, assesses their present utilization, and critically advocates their future in sustainable crop production and the global biofertiliser market. It, therefore, updates our understanding of the evolution of PGPR biofertilisers in crop production. Such information can facilitate the evaluation of their potential and ultimately pave the way for increased exploitation

Keywords: Biofertiliser, Crop production, Evaluation, Sustainable fertiliser



Résumé

Ces dernières décennies ont été marquées par une augmentation de la production agricole afin de répondre à la demande mondiale en alimentation humaine et animale, ainsi qu'en produits pharmaceutiques, liée à la croissance démographique. Les pratiques agricoles conventionnelles dépendent fortement des engrais artificiels, qui ont de nombreux effets néfastes sur la santé humaine et l'environnement. Face à ce constat, les chercheurs en développement durable/agroécologie et les environnementalistes se sont davantage intéressés aux mécanismes de fertilisation agricole durable. Les biofertilisants sont des formulations microbiennes composées de micro-organismes indigènes favorisant la croissance des plantes (PGPM), qui stimulent directement ou indirectement cette croissance par la fixation, la solubilisation et la mobilisation des nutriments du sol, ainsi que par la production d'hormones de croissance et de métabolites séquestrant le fer, appelés sidérophores. Les biofertilisants ont fait l'objet d'études continues, ont été recommandés et ont même été adoptés avec succès pour la production de nombreuses cultures à travers le monde. Ces produits microbiens présentent un potentiel considérable en tant qu'outils de production agricole durable, notamment dans le contexte du changement climatique, en partie alimenté par les engrais artificiels. Malgré l'intérêt croissant pour cette technologie, son plein potentiel n'est pas encore atteint et son utilisation semble encore à ses débuts. Il est nécessaire de faire la lumière sur le passé, l'état actuel et les perspectives d'avenir des biofertilisants afin d'améliorer leur compréhension et leur utilisation. Cette étude évalue l'historique des biofertilisants PGPR, analyse leur utilisation actuelle et défend de manière critique leur avenir dans la production agricole durable et sur le marché mondial des biofertilisants. Elle actualise ainsi notre compréhension de l'évolution des biofertilisants PGPR en agriculture. Ces informations peuvent faciliter l'évaluation de leur potentiel et, à terme, ouvrir la voie à une exploitation accrue.

Mots-clés: Biofertilisant, Production agricole, Évaluation, Engrais durable

INTRODUCTION

The potentials of biofertiliser in crop production for sustainable Agriculture

The global population will be 10 billion people by 2050, thus high pressure will be mounted on the existing food resources (United Nations, 2015). The global agriculture sector has been confronted with increasing challenges in its efforts to adopt environmentally sustainable methods in recent times (Assede *et al.*, 2025). There are concerns about conventional fertilisers' environmental impacts and their contribution to soil degradation; the focus has shifted toward alternative, environmentally friendly solutions (Chakraborty *et al.*, 2025; Odedra *et al.*, 2025).

Although global crop production can be achieved through agricultural intensification, this will escalate

reliance on chemical agro inputs like fertilisers that pose several environmental effects (Vassilev *et al.*, 2015; Abhilash *et al.*, 2016b). Although chemical fertilisers (which are mainly composed of N, P, or K) are widely used in contemporary farming methods, only a small portion (30-40%) of these nutrients is taken up by plants because of low fertiliser-use efficiency (Ye *et al.*, 2025), the remainder is lost to the soil and pollutes the environment. By 2050, it is predicted that the global trend of synthetic N-fertiliser usage will have increased by 1.7 times (Akhtar *et al.*, 2021). Hence, environmental problems are made even more pressing by the enduring presence of radio nuclides and heavy metals in chemical fertilisers (Kelepertzis, 2014)

For instance, chemical fertilisers are extensively associated with greenhouse gas emissions that fuel

global warming and climatic changes (Kahrl *et al.*, 2010; Mapanda *et al.*, 2011; Carmo *et al.*, 2013). Similarly, the eutrophication of several water bodies and the destabilization of aquatic ecosystems have several times been attributed to fertiliser runoffs from agricultural fields (Deepa and Venkateswaran, 2018; Zhang *et al.*, 2018). Ironically, long-term artificial fertilization can also include the overall deterioration of soil productivity and quality through acidification (Neog, 2018; Bai *et al.*, 2020; Yan *et al.*, 2020). Owing to the aforementioned- challenges, the exploration of alternative crop fertilization mechanisms is mounting worldwide in an attempt to develop sustainable food production systems. An innovative and promising solution to these problems has been the development of biofertilisers, which have ushered in a new era in agriculture (Debnath *et al.*, 2019). It is essential to consider the biological health of the soil, nutrient availability, and soil quality while increasing crop production per unit area (Tilman *et al.*, 2011)

The exploration of plant microbiomes has particularly gathered surmountable interest in this regard. Among the most interesting plant microbiomes are the plant growth-promoting Microbes (PGPM) that present several advantageous functions in plant rhizospheres, from nutrients solubilization (Ibarra-Galeana *et al.*, 2017; Borgi *et al.*, 2020; Verma *et al.*, 2020), to suppression of plant diseases (Jayakumar *et al.*, 2021), nitrogen (N₂) fixation (Hara *et al.*, 2020), and improved phytochemical composition (Rizvi *et al.*, 2022a), among others. Probiotics, which are also called Biofertilisers, are microbial formulations of PGPM strains that can either be immobilized or trapped on inert carrier materials to enhance plant growth and soil fertility (Aloo *et al.*, 2022b). Over the decades, considerable strides have been made to understand, investigate, and formulate various PGPM as alternative crop fertilization tools (Barin *et al.*, 2022; Aloo *et al.*, 2022c). The yield of various crops can be increased by

about 25%, and the use of inorganic N and P fertilisers be reduced by about 25-50 and 25% through biofertiliser application (Saber *et al.*, 2012).

The utilization of biofertilisers dates to ancient times when agricultural practices relied on organic amendments to enhance soil fertility. Today, a wide range of naturally occurring microorganisms, including bacteria, fungi, and algae, are referred to as biofertilisers because they stimulate plant development in different ways (Chakraborty and Akhtar 2021). Several developments have been made through the decades, and today, biofertiliser formulations are applied to produce several crops entirely or with reduced usage of artificial fertilisers. Despite these developments, biofertiliser technology is yet to be explored to its maximum potential. It is important to increase our knowledge of biofertilisers and their massive potential in the sustainability of food production systems to increase their utilization. This paper aims to explore the significant strides biofertilisers have made over the years, emphasizing their role as a sustainable and eco-friendly solution for modern crop production.

The review begins by delving into the concept and meaning of biofertilisers, analyzing their adoption rates, differences between biofertiliser and organic fertiliser and exploring the geographical distribution of their application. We aim to highlight successful instances of biofertiliser integration into conventional agricultural practices. Furthermore, we explore the underlying mechanisms through which these microorganisms enhance plant growth, unlocking the intricate interplay between soil-plant-microbe interactions. However, despite their potential, several issues surrounding biofertilisers have hindered their widespread adoption. We critically evaluate the challenges of production, quality control, and formulation, which pose significant obstacles to their large-scale implementation. Additionally, the complex interactions between biofertilisers and other soil

components necessitate a deeper understanding of their behaviour and efficacy in varying agro-climatic conditions.

The concept and definition

Biofertilisers are products that contain living microorganisms that exert direct or indirect beneficial effects on plant growth and crop yield through different mechanisms (Sharma and Kagday *et al.*, 2024).They are organic substances that contain living microorganisms or their metabolites, which can enhance nutrient availability and plant growth by various mechanisms. Biofertilisers are considered an eco-friendly and sustainable alternative to chemical fertilisers (Chakraborty and Akhtar 2021) Biofertilisers can reduce greenhouse gas emissions and the dependence on fossil fuels for fertiliser production (Osorio-Reyes *et al.*, 2023). They help to provide plants with essential nutrients such as nitrogen, phosphorus, and potassium. They can be applied to the soil either by soil application or seed priming, colonize the rhizosphere (Singh *et al.*, 2021) or directly to the plant, and they work by improving the soil's ability to retain nutrients, thus making them more available to plants. Biofertilisers can also help improve soil structure and increase the presence of beneficial microbes in the soil (Sharma *et al.*, 2012). There are several types of Biofertilisers, each of which serves a specific purpose. For example, nitrogen-fixing Biofertilisers can help increase the nitrogen levels in the soil (Shridhar 2012). In contrast, phosphorus-solubilizing biofertilisers can help make the soil's phosphorus more available to plants (Kalayu 2019). Understanding the basics of biofertilisers is essential for any farmer looking to transition to organic farming or enhance the sustainability of their existing operation. By using Biofertilisers, farmers can improve soil health, increase crop yields, and reduce the environmental impact of their farming practices.

What is bio-fertiliser?

A bio-fertiliser is simply a substance that contains living microorganisms which, when applied to the soil, a seed or plant surface, colonizes the rhizosphere and promotes growth by increasing the supply or availability of nutrients to the host plant (Vessey, 2003). A bio-fertiliser is a modernized form of organic fertiliser into which beneficial microorganisms have been incorporated (Swathi, 2010). According to Hari and Perumal (2010) bio-fertiliser is most commonly referred to as selected strains of beneficial soil microorganisms cultured in the laboratory and packed in suitable carriers. In a large sense, the term biofertiliser may be used to include all organic resources for plant growth which are rendered in available form for plant absorption through microorganisms or plant associations or interactions (Khosro *et al.*, 2012)

Importance of bio-fertilizers

Bio-fertilisers play an important role in improving the fertility of the soil. In addition, their application to soil improves the structure of the soil and minimizes the use of chemical fertilisers. Under low-land conditions, the application of blue-green algae (BGA) plus Azospirillum proved significantly beneficial in improving the yield of grain. Bio-fertilisers inoculation with Azotobacter and Rhizobium and Vesicular Arbuscular Mycorrhiza gave the highest increase in straw and grain yield of wheat plants with rock phosphate as phosphate fertiliser (Ritika *et al.*, 2014). Azolla is inexpensive, economical, and eco-friendly, which provides benefits in terms of carbon and nitrogen enrichment of soil. It was recorded that microorganisms such as Bacillus subtilis, Thiobacillus thioxidans, and Saccharomyces species can fix atmospheric nitrogen symbiotically, and about 80-90% nitrogen demand could be supplied by soya bean through symbiosis (Ritika *et al.*, 2014). Biocontrol, a modern approach to disease management, can play a

significant role of bio-fertiliser in agriculture. Trichoderma-based bio-fungicides and fertiliser has been found promising to control root rot of mung bean (Ritika *et al.*, 2014). Growth, yield, and quality parameters of certain plants significantly increased with bio-fertilisers containing bacterial nitrogen fixers, phosphate and potassium solubilizing bacteria, and microbial strains of some bacteria (Khosro *et al.*, 2012). The importance of biofertilisers are highlighted below: Secretion of plant growth hormones which help in plant growth, protection of the plant against attack by pathogens, improvement soil fertility, no special care is necessary while using bio-fertiliser, reduction in the use of chemical fertilisers, bio-fertilisers are cost effective compared to synthetic fertiliser, promotes growth of plants, restore the soil's natural, nutrient cycle and build soil organic matter and provides protection against drought.

The role of bio-fertilisers in enhancing plant tolerance to environmental stress

Abiotic and biotic factors are the major constraints that affect the productivity of crops. Many tools of modern science have been widely applied for crop improvement under stress, of which the role of plant growth-promoting rhizobia PGPRs as bio-protectant has become of paramount importance in this regard (Chang and Yang, 2009). According to Hussain et al. (2002),Rhizobium trifoli inoculated with Trifolium alexandrium showed higher biomass and an increased number of nodulations under salinity stress conditions. Pseudomonas aeruginosa has been shown to withstand biotic and abiotic stress. Pseudomonas putida RS-198 enhanced germination rate and several growth parameters, including plant height, fresh weight, and dry weight of cotton under conditions of alkaline and high salt via increasing the rate of uptake of k⁺, Mg²⁺, and Ca²⁺ and by decreasing the absorption of Na⁺. Few strains of Pseudomonas conferred plant tolerance via 2, 4-diacetylphloroglucinol. Mycobacterium phlei

provides tolerance to high temperatures and salinity stress. It has been demonstrated by Ansari *et al.* (2013) that inoculation of plants with Arbuscular mycorrhiza fungi also improves plant growth under salt stress. Ansari *et al.* (2013) also observed that a root endophytic fungus, Piriformospora indica, was found to defend the host plant against salt stress. A combination of AM fungi and nitrogen-fixing bacteria helps the legume plants in overcoming drought stress. Application of Pseudomonas Spp to basal plants under water stress improves their antioxidant and photosynthetic pigment content. Pseudomonas Spp was found to have a positive effect on the seedling growth and seed germination under water stress (Liddycoat, 2009). Ruiz-Sanchez *et al.* (2010) reported that the photosynthetic efficiency and the anti-oxidative response of rice plants subjected to drought stress were found to increase after inoculation of arbuscular mycorrhiza. The beneficial effect of mycorrhizae has also been reported under both drought and saline conditions. PGPRs as biological agents proved to be one of the alternatives to chemical agents for providing resistance against various pathogens' attacks. Apart from acting as growth-promoting agents, they can provide resistance against pathogens by producing metabolites (Backman and Sikora, 2008). Bacillus subtilis GBO can induce defence related pathways. Bacillus subtillis N11, along with mature compost, was found to control Fusarium infestation on banana root. By and large, the exploitation of PGPRs was found to be very significant in managing spotted wilt viruses in tomato, cucumber mosaic virus of tomato and pepper, and banana bunchy top virus. In some cases, it was observed that along with bacteria, mycorrhizae can also confer resistance against fungal pathogens and inhibit the growth of many root pathogens such as R. solani and Pythium Spp.

Biofertiliser as a Phytostimulator or Biostimulant

Still, other biofertilisers can promote plant growth

through phytohormone production and plant growth stimulation in many ways. Such biofertilisers are largely known as *phytostimulators* owing to the various roles they play in stimulating the growth of crops through the production of *phytohormones*. The most common *phytohormones* are *auxins*, *gibberellins*, and *cytokinin*. Although very small amounts of *phytohormones* are produced by PGPR, they are still very crucial for plant metabolic processes, including those that modulate plant growth (Kalimuthu *et al.*, 2019; Haerani *et al.*, 2021) and plant tolerance to various abiotic stresses (Mahmoody and Noori, 2014; Santhi *et al.*, 2021). Among the most promising PGPR that can function as biofertilisers due to phytohormone production are *Azospirillum* (Coniglio *et al.*, 2019) and *Bacillus* spp. (Kang *et al.*, 2019; Bandopadhyay, 2020), and many others. Owing to the importance of phytostimulation, such PGPR are viable candidates for PGP as biofertilisers, especially if they can also solubilize plant nutrients and/or fix N to improve plant nutrition

Difference between bio-fertiliser and organic fertiliser

Before now, the term bio-fertiliser was used to include organic fertiliser. However, technically, there is a big difference between them. Vishal and Abhishek, (2014),to distinguish between bio-fertiliser and organic fertiliser said "bio-fertilisers are microbial inoculants consisting of living cells of microorganisms like bacteria, algae, fungi, alone or in combination, which may help in increasing crop productivity. Biological activities are markedly enhanced by microbial interactions in the rhizosphere of plants. Organic fertilisers, on the other hand, are obtained from animal sources such as animal manure or plant sources like green manure.

CAUTION IN THE USE OF BIO-FERTILISERS

- a) Never mix bio-fertilisers with nitrogen fertilisers.
- b) Never apply bio-fertilisers with fungicides.

- c) Never expose bio-fertilisers to sunlight directly.
- d) Bio-fertilisers are stored at room temperature, not below 0 °C and above 350 °C
- f) Do not keep the used solution overnight (Harriet al., 2010)

Soil fertility

Soil refers to the part of the earth on which plants grow (Purves *et al.*, 2000). It consists of three layers: topsoil, subsoil, and parent material. However, we are more concerned with the topsoil since it is the part that supports plant growth. It contains minerals, air, water, living organism and inorganic and organic matter, all of which must be in a particular ratio with at least a medium pH to constitute a fertile soil. According to Purves *et al.* (2000), a good quality soil is one that is 45% minerals (sand, silt, and clay), 25% water, 25% air, and 5% organic and living matter. The mineral portion of a soil, which makes up half of the volume, contains about 93% silica, aluminium and iron oxides: 4% calcium, potassium, and magnesium oxides, and 3% titanium, sodium and a very small amount of nitrogen, sulphur, phosphorous, boron, manganese, zinc, copper, chlorine, molybdenum and many other elements. However, of all these minerals, only fourteen are essential to plant and these are called essential elements (Purves *et al.*, 2000). According to Barak (Barak 1999), the essential nutrients are divided into micronutrients and macronutrients. The macronutrients are required in larger quantities, whereas the micronutrients are required in small quantities by plants. The first six elements shown in Table 1 are macronutrient while the rest are micronutrients. The macronutrients are further divided into primary macronutrients (those that are always limited in the soil) and secondary macronutrients (those that are rarely limited). The primary nutrients are nitrogen, phosphorous and potassium.

Nitrogen:

Nitrogen is one of the primary macronutrients that is required by plants in large quantities. Its functions include formation of base pair for RNA and DNA, formation of phosphate group of protein (example hemp group of chlorophyll) and hormones such as cytokines, metal uptake (*phytosiderorphores*), transport in xylem and phloem (example copper with amines), as *osmoregulation* (example in lettuce and spinach), *alkaloids*, *miscobiochemicals* e.g., mescaline, quinine (Barak, 1999). Nitrogen is absorbed by plants in the form of nitrates, ammonium, and sometimes urea (Ifokwe *et al.*, 1988) and is added to the soil through fertiliser, biological nitrogen fixation, rainfall and thunder, and decomposition of organic matter. According to Barak (1999) a plant deficient in nitrogen shows the following symptoms: stunted growth and light green or yellow leaves. Severe deficiency symptoms include necrosis starting from the tip of the older leaves and developing a 'v' pattern.

Phosphorus:

Phosphorus is needed in relatively large amounts, but at a quantity lower than that of nitrogen and potassium. It promotes legume growth and yield, nodule number, and nodule mass. Its functions include *Phospholipids* in the membrane, *phosphoproteins* for life functions, and improvement of crop yield and quality. It is important in seed formation. Analysis has shown that it forms a substantial component of seeds and fruits (Scalenghe *et al.*, 2012). Phosphorus is absorbed by plants in the form of phosphates and is added to the soil through fertilisers, bone meal, and superphosphates. Barak (1999) stated that phosphorus is phloem mobile and its deficiency symptoms are evenly spread throughout the plant. However, stunted growth and late maturity are often associated with its deficiency. In severe cases, grassy species such as corn show reddening of the leaves. According to Scalenghe *et al.* (2012), excess phosphorus is not good as plants cannot

properly assimilate it because most phosphorus is in inorganic form. Excess phosphorus is characterized by early maturation of plants and low crop yield in plants.

Potassium

Plants' requirement for this element is only second to that of nitrogen. Potassium influences the water economy and crop growth through its effects on water uptake, root growth, maintenance of turgor, transpiration, and stomatal regulation (Mfilinge *et al.*, 2014). The functions of potassium include the following. It enhances the cold endurance of some plants as well as their resistance to fungal and bacterial diseases; It intensifies the synthesis of high molecular carbohydrates resulting in cell walls of the straw of cereals thicker, It catalyses the activities of some enzymes and promotes the synthesis and accumulation of certain vitamins in plants (Thiamin and Riboflavin), It is essential for the activity of guard cells, It aids in photosynthesis, building up of protein and improving fruit quality (Ifokwe *et al.*, 1988, Barak ., 1999). Potassium is absorbed by plants in the form of potassium ions, which are insoluble in water. It is added to the soil by fertiliser, decaying organic matter, and wood ash. According to Ifokwe (1988), potassium deficiency upsets the plant's metabolism, inhibits the activity of some enzymes, and disrupts carbohydrate and protein metabolism. The author also stated that inadequate potassium supply reduces the viability of seeds, makes plants more prone to diseases, and, when harvested, they become difficult to preserve in marketable conditions. Other elements required by plants in large quantities include oxygen, carbon, and hydrogen. These are obtained through air and water and therefore are bountiful in nature (Barak 1999).

Global demand for biofertiliser

The use of biofertilisers has gained significant attention in recent times due to the increasing focus on sustainable agriculture and environmental

management, with rhizobia and PSB being the most in-demand biofertilisers (Nath Bhowmik and Das 2018). Rhizobia accounts for approximately 79% of the global market share, while PSB holds a 15% share (Garcha, 2023). India and China have significant areas under organic farming, with around 4.2 million hectares and 167 million hectares, respectively (Horo and Das, 2019). This trend has led to an increased demand for biofertilisers in these regions, particularly in India, where the government has actively encouraged organic farming through various policies and initiatives. The use of biofertilisers offers several benefits, including increased soil fertility, reduced soil erosion, and improved crop yield, making them an attractive option for farmers looking to adopt sustainable farming practices. Around the world, biofertilisers are growing in popularity, particularly in developed nations such as Spain, Italy, and Germany, where they are seen as a sustainable alternative to chemical fertilisers (Raimi *et al.*, 2021; Ibanez *et al.*, 2023).

According to market analysis, the global biofertiliser market had a value of US\$1.06 million in 2016 and is projected to reach US\$3.8 billion with an 11.2% compound annual growth rate between 2020 and 2025 (Raimi *et al.*, 2021; Aloo *et al.*, 2022a). The global biofertiliser market is forecast to be valued at USD 2.3 billion in 2019 and is expected to increase at a compound annual growth rate (CAGR) of 11.6% between 2020 and 2027, according to a Grand View Research report (Raut *et al.*, 2023). The biofertiliser market is segmented by product type, crop type, application, and region. The product type segment includes nitrogen-fixing, phosphate-solubilizing, potash-mobilizing, and others. The nitrogen-fixing biofertilisers accounted for the largest market share in 2019, owing to their wide application in various crops and their ability to fix atmospheric nitrogen into plant-available forms (Soumare *et al.*, 2020). These biofertilisers are expected to grow at the fastest pace over the predicted period because they can increase

phosphorus availability and uptake in low-phosphorus soils.

Types of bio-fertilisers and how they work

Bio-fertilisers are classified into different types depending on the type or group of microorganisms they contain. The different types of bio-fertilisers include:

1) Nitrogen fixing bio-fertilisers (NFB):

Nitrogen-fixing biofertilisers are currently the most common in the global market and their demand is anticipated to grow by a further 11.9% compounding annual growth rate (CAGR) to reach about USD 4.5 billion by 2026 up from the current USD 2.1 billion (Markets and Markets, 2020). Nitrogen-fixing biofertilisers comprise bacteria that carry out biological N₂ fixation (BNF) and boost soil N supply to crops. The legume N₂-fixing rhizobia have been researched for decades and shown to increase the quantity of fixed N in inoculated plants relative to uninoculated ones (Koskey *et al.*, 2017; Sanyal *et al.*, 2020; Gedamu *et al.*, 2021; Ketema and Tefera, 2022). Previous inputs of fixed N for red clover, alfalfa, soybean, pea, and cowpea were estimated to range from 23 to 335 kg ha⁻¹ year⁻¹ (Thies *et al.*, 1995; Wani *et al.*, 1995). The variabilities in terms of quantities of fixed N depend much on the type of legume-rhizobia symbiosis which is dictated by several factors like the legume cultivars and genotypes (Gunnabo *et al.*, 2020; Riah *et al.*, 2021), as well as the geographical distributions (Ramonedá *et al.*, 2020).

Earlier studies by Melchiorre *et al.*, (2011) and Hungria *et al.*, (2006) both established that the yield of grains in Brazil, and Argentina, respectively, could reach close to 5 t ha⁻¹ each season through rhizobia-mediated BNF. Similarly, annual N₂ fixation rates of approximately 40 kg N ha⁻¹ are documented in Australian soils (Unkovich and Baldock, 2008). Nevertheless, the contribution of symbiotically fixed N in crop fields largely remains unestablished. More

research is necessary, especially for crops like cereals, vegetables, and tubers, considering how they contribute to the bulk of human food.

Examples include Rhizobium Spp., Azospirillum Spp. and blue-green algae; these work by fixing atmospheric nitrogen and converting them to organic (plant usable) forms in the soil and root nodules of legumes, thereby making them available to plants. Nitrogen fixing bio-fertilisers are crop specific bio-fertilizers (Choudhury *et al.*, 2004).

2) Phosphate solubilizing bio-fertiliser (PSB):

Examples include Bacillus Spp., Pseudomonas Spp. and Aspergillus Spp. These work by solubilizing the insoluble forms of phosphate in the soil, so that plants can use them. Phosphorus in the soil occurs mostly as insoluble phosphate which cannot be absorbed by plants (Gupta, 2004). However, several soil bacteria and fungi possess the ability to convert these insoluble phosphates to their soluble forms. These organisms accomplish this by secreting organic acids, which lower the pH of the soil and cause the dissolution of bound forms of phosphate, making them available to plants (Chang and Yang, 2009).

3) Phosphate-mobilizing bio-fertilisers (PMB):

Examples are Mycorrhiza. They work by scavenging phosphates from soil layers and mobilizing the insoluble phosphorus in the soil to which they are applied. Chang and Yang (2009) stated that phosphorus-solubilizing biofertiliser (PSB) sometimes acts as a phosphate mobilizer. Phosphate-mobilizing bio-fertilisers are broad-spectrum bio-fertilisers.

4) Plant growth-promoting bio-fertiliser (PGPB):

Examples of plant growth rhizobacteria are Pseudomonas Spp. etc: these work by producing hormones and anti-metabolites which promote root growth, decomposition of organic matter, which helps

in mineralization of the soil, thereby increasing availability of nutrients and improving crop yield (Khosro *et al.*, 2012, Bhattacharyya *et al.*, 2012). PGPB are crop-specific bio-fertilisers.

5) Potassium solubilizing bio-fertiliser (KSB):

Examples include Bacillus Spp and Aspergillus niger. Potassium in the soil occurs mostly as silicate minerals, which are inaccessible to plants. These minerals are made available only when they are slowly weathered or solubilized. Potassium-solubilizing microorganisms solubilize silicates by producing organic acids, which cause the decomposition of silicates and help in the removal of metal ions, thereby making them available to plants. Potassium-solubilizing bio-fertilisers are broad-spectrum bio-fertilisers.

6) Potassium mobilizing bio-fertiliser (KMB):

An example of potassium mobilizing bio-fertiliser is Bacillus Spp. These work by mobilizing the inaccessible forms of potassium (silicates) in the soil. Some phosphate-solubilizing bio-fertilisers, such as Bacillus Spp and Aspergillus Spp. has been found to mobilize potassium and solubilize phosphorus.

7) Sulfur-oxidizing bio-fertiliser (SOB):

An example of a sulphur-oxidizing microorganism is Thiobacillus Spp. These work by oxidizing sulfur to sulfates, which are usable by plants.

MICROORGANISMS USED IN BIO-FERTILISER

Organisms that are commonly used as bio-fertiliser components include nitrogen fixers (N-fixers), potassium solubilizers (K-solubilizers), phosphorus solubilizers (P-solubilizers), phosphorus mobilizers (P-mobilizers), used solely or in combination with fungi. Most of the bacteria used in bio-fertilisers have a close relationship with plant roots. Rhizobacterium has symbiotic interactions with legume roots, and Rhizobacteria inhabit root surfaces or rhizosphere soil

(Khosro 2012). The phospho-microorganisms, mainly bacteria and fungi, make insoluble phosphorus available to the plants (Gupta, 2004). Several soil bacteria and a few species of fungi possess the ability to convert insoluble phosphate in soil into soluble forms by secreting organic acids. These acids lower the soil pH and bring about the dissolution of bound forms of phosphate (Gupta 2004). While Rhizobium, blue-green algae, and Azolla are crop-specific, bio-inoculants such as *Azotobacter*, *Azospirillum*, *phosphorus-solubilizing* bacteria (PSB), and *Vesicular Arbuscular Mycorrhiza* (VAM) could be regarded as broad-spectrum bio-fertilisers (Gupta 2004). VAM are fungi that are found associated with most crops and enhanced accumulation of plant nutrients (Khosro, 2012; Wani *et al.*, 2013). It has been suggested that VAM stimulate plant by physiological effects or by reducing the severity of diseases caused by soil pathogens. Examples of free-living nitrogen-fixing bacteria are obligate anaerobes, *Clostridium pasteurinnum* obligate aerobes, facultative anaerobes, *photosynthetic* bacteria, *Rhodobacter*, cyanobacteria (*Azotobacter*), and some *Methanogens*. The most used *K-solubilizer* is *Bacillus mucilaginous*, while P-solubilizers are *Bacillus megaterium*, *Bacillus circulans*, *Bacillus subtilis*, and *Pseudomonas straita* (Gupta 2004)

THE CURRENT STATE OF BIOFERTILISER

There is a burgeoning literature on the current application of microbial products as *biofertilisers* and agricultural inputs. Nearly 170 establishments in 24 countries commercialize biofertilisers and possess factories that produce and market microbe-based fertilisers at both small and large scales (Bharti *et al.*, 2017). The marketing of *rhizobial inoculants* has been practiced for several decades now to partially eliminate the application of artificial fertilisers (Paudyal and Gupta, 2018). However, the full potential of many biofertilisers is largely untapped. Likewise, biofertiliser commercialization remains low globally,

albeit steadily increasing. In developed countries where artificial agricultural inputs are a bit cheap, the use of PGPR is less prioritized but is albeit growing. In 2013, the highest demand for biofertilisers was highest in North America and projections were that the entire Asia-Pacific biofertiliser market would show the maximum growth from 2014 to 2019 and lead in biofertiliser consumption worldwide (Markets and Markets, 2014). The consumption of biofertilisers is reportedly growing in countries such as Canada, Argentina, China, India, Europe, and the United States of America (USA) due to tax exemptions and input subsidies, among other incentives (Markets and Markets, 2019). Such approaches have generally served to expand the global biofertiliser market, but more efforts are still required. The advancement of research around the globe on the diversity, functions, and potentials of native rhizobacteria has stimulated the selection and isolation of efficient PGPR, and several biofertiliser formulations are already produced and commercialized for use in different countries across the globe. The most progressive and dominant biofertiliser market in the world is Europe, where biofertiliser demand has grown at a CAGR of 12.3% from approximately US\$2566 million in 2012 to US\$4582 million in 2017 (Chandrasekhar, 2014). The global biofertiliser market was worth US\$1.06 million in 2016 and was estimated to hit US\$2 billion in 2019 and over US\$3.8 billion in 2026, at a CAGR of 11.2% (Markets and Markets, 2020). The global increase in demand for biofertilisers has greatly been greatly influenced by the growing demand for organic food products. Although there exist many reports on the formulation and/or commercialization and application of rhizobacterial biofertilisers in several parts of the world, only a few reports indicate their application and commercialization in Africa. The PGPR inoculant technology has little or no impact on crop productivity in developing countries since it is either not practiced or the poor quality of available inoculants (Bashan, 1998).

According to Aloo *et al.* (2021), the potential benefits of biofertilisers have largely been untapped in Africa due to inadequate regulatory frameworks and several other challenges. Most biofertilisers are commercialized for use in Asia, Europe, and the USA but in Africa, most commercialization and application occur only in South Africa. In East Africa, the production and use of biofertilisers are pronounced in Kenya, where Biofix is the manufacturer of Biofix, which can effectively inoculate 15kg of common bean seeds per ha at approximately US\$1.25 in comparison to 90kg of artificial N fertiliser required for the same number of seeds per ha. at US\$12.50 (Raimi *etal.*, 2021). However, Biofix and other biofertilisers are still largely underutilized in Kenya, probably due to a lack of awareness and other technology adoption challenges. Current and future initiatives are anticipated to improve the uptake of biofertilisers in Africa (Raimi *et al.*, 2021). However, more efforts are needed to boost the consumption of these microbial products and promote the sustainability of global food production systems (Aloo *et al.*, 2021). The worldwide market for biofertilisers is presently largely dominated by legume and N2-fixing inoculants (Vassilev *et al.*, 2015). While rhizobial inoculants currently dominate the global biofertiliser market, PSB and other bioinoculants occupy less than 30% altogether (Transparency Market Research, 2022). Nevertheless, P-, K-, and Zn-based biofertilisers are now developing into significant bioinoculants to address soil nutrient deficiencies, and KSM are already commonly used as inoculants in some countries with K-deficient croplands (Teotia *et al.*, 2016). India is reportedly the 4th largest consumer of K bioinoculants globally, while countries like Brazil, the USA, and China come first in the overall consumption of these microbial products (Matich, 2016). Unlike rhizobial biofertilisers, PSB, like *Pseudomonas*, *Bacillus*, and diazotrophs like *Azospirillum*, have not been used as much nor at a large scale (Lesueur *et al.*, 2016). Most of the commercially

available non-rhizobial PGPR inoculants consist of *Azospirillum* as free-living N₂ fixers or *Bacilli* as PSB (Herrmann and Lesueur, 2013). The application of non-rhizobial biofertilisers has a less significant impact on global food production, probably because of several bottlenecks that exist in biofertiliser uptake and use relative to well-documented PGP functions. Yet, PGPR like PSB, are essential candidates for improving legume P nutrition for efficient nodulation (Zaidi *et al.*, 2017). The global biofertilisers market for crop production is projected to grow from US\$2.02 billion in 2022 to US\$4.47 billion by 2029, at a CAGR of 12.04% from 2022 to 2029 (Fortune Business Insights, 2022). Still, there is a need for more efforts for adequate market infiltration and application.

The future of biofertilisers

The incorporation of biofertilisers as fundamental components of agricultural practices is quickly gathering momentum globally. These microbial products are already in use in some countries and are expected to become more popular in the future. The global and future expansion of the biofertiliser market will largely be driven by the need to increase food production sustainably. With an ever-increasing demand for organic food products, growing awareness of sustainable agricultural practices, and promotion of cleaner production methods for reducing soil contamination, land degradation, and water pollution, the market growth for biofertilisers will continue to grow over the coming years (Abhilash *et al.*, 2016a; Anand *et al.*, 2022; Vaishnav *et al.*, 2022). Forecasts are that the present global market for biofertilisers, which was approximated at US\$396 million in 2018, will grow at a CAGR of 10.9% to escalate to US\$4,448.97 million (or roughly US\$4.45 billion) by 2028 (Vintage Market Research, 2022). Further indications are that the global biofertiliser market, which was valued at close to US\$ 3.0 billion in 2020, will grow at a CAGR of 12.2% and reach about US\$5 billion by 2031

(Transparency Market Research, 2022). The number of investigations targeting the isolation, identification, and evaluation of the capacity of PGPR with the potential of being transformed into inoculants for a variety of crops is equally expanding (Koskey *et al.*, 2017; Anand *et al.*, 2022; Aloo *et al.*, 2022c). It is, therefore, realistic to expect that widespread biofertiliser usage will soon offer countless approaches to the progression of sustainable crop production systems. For the extensive utilization of biofertilisers, proper regulatory and legal frameworks will be required in place of the existing ones that are currently stringent and hinder their proper utilization. Fortunately, regulatory authorities are increasingly encouraging the implementation of alternative crop fertilization mechanisms to promote the development of sustainable agricultural technologies. Recognizing the need for a specific legislative framework for biofertilisers in Europe, the European Commission has proposed to amend existing regulations (European Parliament and Council of the European Union, 2016). Such initiatives will eventually relax the stringent regulatory frameworks and enable the widespread adoption of these microbial resources. While several of the existing biofertilisers are mainly composed of natural rhizobacterial strains chosen for their PGP qualities, the development of genetically-modified inoculants that are likely to be more efficient at plant growth stimulation is required. Still, the biggest hurdle will be for scientists to convince society and regulatory authorities worldwide that such genetically engineered organisms are harmless. Our current ability to manipulate and exploit the plant microbiome in situ similarly remains limited, and more investigations are required to facilitate their large-scale application and commercialization. The inoculant industry is faced with various challenges in making formulations with prolonged shelf lives. Progress into developing formulations with improved shelf lives, broad spectra of action, and reliable field performance will therefore

hasten the commercialization of this technology (Nakkreen *et al.*, 2005). In this regard, new approaches should be evaluated to develop formulations with longer shelf lives. Micro-encapsulation is one viable approach, but most experiments in this regard have been restricted to laboratories and the standardization of this technology for industrial and field applications should be pursued. The future of biofertiliser technology depends a lot on developing efficient PGP strains.

CONCLUSIONS

The dependence on chemical fertilisers and pesticides has encouraged the thriving of industries that are producing life-threatening chemicals, which are not only hazardous for human consumption but can also disturb the ecological balance. The attention is now shifting from consuming food grown with chemical fertilisers to food grown with organic fertilisers due to harmful effects posed to both human and other living organism, it has also been linked to various ailments in humans and livestock. Biofertilisers can help solve the problem of food needs of the ever-increasing global population while not polluting the environment. It is important to realize the useful aspects of bio-fertilisers to apply it in modern agricultural practice. The application of bio-fertilisers containing beneficial microbes largely promotes crop productivity. These potential biological fertilisers would play a key role in the productivity and sustainability of soil and protect the environment as eco-friendly and cost-effective inputs for the farmers. Using biological and organic fertilisers, a low-input system can help to achieve the sustainability of farming. The new technology, when developed using the tool of molecular biotechnology, can enhance the biological pathways of production of phytohormones if identified and transferred to the useful plant growth-promoting rhizobacteria. This technology will help provide relief from environmental stresses. However, the ignorance regarding improved

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Evaluation of Biofertiliser as a Sustainable Fertiliser in Crop Production
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Influence of Ibadan Brewery Waste-Based Compost on the Growth and Yield of Cabbage

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ABSTRACT

In Nigeria, waste management and disposal have become a significant cost factor and an important aspect in the running of a brewery operation. Composting brewery waste could be a major way of disposing of the waste, and it could be a good source of organic fertilizers for crop production. This study aimed to assess the influence of Ibadan Brewery Waste-Based Compost (IBWBC) on the yield of cabbage and on the chemical properties of soil. The experiment was conducted at the Organic Vegetable Garden Teaching and Research Farm, University of Ibadan, Ibadan. The field study was laid out in a Randomized Complete Block Design with two treatments and four replicates. A nursery operation, which lasted for 4 weeks, began the field trial; this was later transplanted. There were sixteen beds measuring 1.8 m x 2.4 m for each and were spaced 50 cm apart. The IBWBC was obtained from an ongoing experiment on the farm, and the application was done two weeks before transplanting. Harvesting was done after 13 weeks of transplanting. Growth and yield parameters, as well as soil properties of the experimental site, before and after planting, were determined. The yield of cabbage planted with IBWBC was 14.81t/ha, which was significantly higher than the control (4.93 t/ha), where no fertiliser was used. The fertilizer application increased the organic matter of the soil and influenced other chemical properties of the soil after planting. The pH of the soil was in the neutral zone. In conclusion, Ibadan brewery waste-based composts can serve as a good organic fertilizer in cabbage production and can be used to improve the fertility status of the soil over time.

Keywords: Brewery waste, Cabbage, Compost, Ibadan brewery waste-based composts, and Soil fertility.



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RÉSUMÉ

Au Nigéria, la gestion et l'élimination des déchets représentent un poste de dépenses important et un aspect essentiel de l'exploitation d'une brasserie. Le compostage des déchets de brasserie pourrait constituer une solution efficace pour leur élimination et une source intéressante d'engrais organiques pour les cultures. Cette étude visait à évaluer l'influence du compost à base de déchets de brasserie d'Ibadan (IBWBC) sur le rendement du chou et les propriétés chimiques du sol. L'expérimentation a été menée à la ferme pédagogique et expérimentale de l'Université d'Ibadan, à Ibadan. Le dispositif expérimental était un bloc complet randomisé à deux traitements et quatre répétitions. Une phase de pépinière de quatre semaines a servi de point de départ à l'essai, suivie d'un repiquage. Seize planches de 1,8 m x 2,4 m, espacées de 50 cm, ont été aménagées. L'IBWBC provenait d'une expérimentation en cours sur la ferme et a été appliqué deux semaines avant le repiquage. La récolte a eu lieu 13 semaines après le repiquage. Les paramètres de croissance et de rendement, ainsi que les propriétés du sol du site expérimental, ont été déterminés avant et après la plantation. Le rendement du chou cultivé avec le compost à base de déchets de brasserie d'Ibadan (IBWBC) était de 14,81 t/ha, soit significativement supérieur à celui du témoin (4,93 t/ha) sans apport d'engrais. L'engrais a augmenté la teneur en matière organique du sol et a influencé d'autres propriétés chimiques de celui-ci après la plantation. Le pH du sol était neutre. En conclusion, le compost à base de déchets de brasserie d'Ibadan peut constituer un bon engrais organique pour la production de choux et contribuer à améliorer la fertilité du sol sur le long terme.

Mots-clés: Déchets de brasserie, Chou, Compost, Compost à base de déchets de brasserie d'Ibadan, Fertilité du sol.

Introduction

An increase in industrial activities has led to pollution of our major rivers and streams in Nigeria, including the streams in a densely populated area of Ibadan (Ibekwe *et al.*, 2004). Waste management and disposal have become a significant cost factor and an important aspect in the running of a brewery operation (Fillaudeau *et al.*, 2006). Every brewery tries to keep waste disposal costs low, whereas the legislation imposed for waste disposal by the authorities becomes more stringent (Knirsch *et al.*, 1999). An alternative use of brewery waste, which could reduce both waste disposal costs and environmental pollution, is its utilisation in composting as a source of organic fertiliser. This approach is particularly important because the availability of alternative organic fertiliser sources remains a major challenge in most organic crop production systems, and it could also contribute to improving the fertility status of many Nigerian soils. The challenge of improving the fertility and increasing the productivity of the soil for increased agricultural

production has become significant (Azagaku and Anzaku 2002). The status of soil fertility in the tropics is therefore of considerable importance for food security, given the increase in global population, with most of this growth occurring in the tropics (Thangavel *et al.*, 2017). An adequate nutrient supply is an essential factor in plant growth; plants are likely to grow well and produce high yields (Fageria *et al.*, 2008). Organic sources of plant nutrients, such as organic amendments could remain the principal sources for the maintenance of soil fertility and environmental quality, and this may also be accomplished through the application of fertilisers (Aytenuw *et al.*, 2020).

Organic fertilizers (such as manure and compost) are valuable for any farming operation and have been used for centuries to supply needed nutrients for crop growth. Manure and compost do not only supply many nutrients for crop production, including micronutrients, but they are also major sources of organic matter (Smith *et al.*, 2007). Increasing soil organic matter improves soil structure, increases the

water-holding capacity of coarse-textured sandy soils, improves drainage in fine-textured clay soils, provides a source of slow-release nutrients, reduces wind and water erosion, and promotes the growth of earthworms and other beneficial soil organisms. (Favoino and Hogg 2008; Albaladejo *et al.*, 2008). Adding compost to soil increases soil fertility and cation exchange capacity (Ndubuaku and Lucas 2000). Compost, added to agricultural soil as a fertilizer to improve soil fertility and promote the growth of crops and microorganisms, and as a soil amendment to relieve heavy metal pollution (Huang *et al.*, 2016). Compost has been used to increase the yield of crops, especially vegetables such as amaranth, celosia, pepper, etc. (Oworu *et al.*, 2009; Komolafe *et al.*, 2021)

Cabbage (Brassica oleracea L.), a member of the Cruciferae and a useful vegetable, belongs to the genus Brassica. This group may be cultivated for edible qualities but also grown ornamentally for its colourful leaf forms. (Jim and Tony, 2006). The health benefits of cabbage, such as treatment for constipation, obesity, skin disorders, heart disease, rheumatism, eye disorders, aging, etc. has made it a sought-after crop (Grubben and Denton, 2004). Increasing the availability of high-quality cabbage throughout the year and reducing its price requires the use of organic fertilizers such as compost. However, much work has not been done on the use of brewery waste-based compost as a fertiliser source on plant growth, yield, and soil properties.

The objectives of this study are to determine the effects of brewery waste-based composts on the growth and yield of cabbage, and to determine the effects of brewery waste-based compost on some fertility properties of the soil.

MATERIALS AND METHOD

Experimental sites

The experiment was carried out at the Organic Vegetable Garden Teaching and Research Farm. It is in

the derived savannah zone of Western Nigeria, which lies between latitude 7 ° 24 'N and longitude 3 ° 54' E with an elevation of 62 m above sea level. The mean monthly temperature ranges between 24 °C and 30°C and the mean annual rainfall ranges between 1800 mm and 2100 mm. The soil texture ranges from sandy to loamy sand, which is slightly acidic. The nursery exercise was carried out at the screen house of the Department of Agronomy, University of Ibadan (70 24'N, 3054'E, 234m above sea level).

Sources of materials: The compost used was obtained from an ongoing experiment at the teaching and research farm of the University of Ibadan. Seeds were obtained from PIONEER Seeds.

Experimental design, methodology, and treatments

The experiment was conducted between October and December 2016, following the establishment of cabbage seedlings in a nursery for four weeks in September 2016. The study was laid out using a randomized complete block design (RCBD) with four replications. Each experimental plot measured 9.2 m × 11.6 m and comprised sixteen beds, with individual beds measuring 1.8 m × 2.4 m and spaced 50 cm apart. Two treatments were evaluated: Ibadan Brewery Waste-Based Compost (IBWBC) and a control treatment without fertilizer application. Cabbage (Brassica oleracea var. capitata) was used as the test crop. The compost was applied at a rate equivalent to 200 kg N ha⁻¹, with the first application incorporated into the soil two weeks before transplanting and the second applied as a top dressing at eight weeks after transplanting. Seedlings were transplanted into the main field at a spacing of 0.6 m between rows and 0.30 m within rows, at a depth of approximately 0.05 m, resulting in sixteen plants per bed. Routine agronomic practices were carried out throughout the experimental period; weeds were controlled manually, and irrigation was applied as required to maintain adequate soil

moisture. Insect pests and rodents were controlled five weeks after transplanting using neem oil applied at a rate of 10 mL per litre of water. Harvesting of cabbage heads was carried out at thirteen weeks after transplanting. Experimental design and treatments: The experiments were laid out in a randomized complete block design (RCBD) with four replications. The plot size was 9.2 m x 11.6 m with sixteen beds. Each bed was 1.8 m x 2.4 m, spaced 50 cm apart.

Treatments: Ibadan Brewery Waste-Based Compost (IBWBC) and Control- no fertilizer added were the treatments used.

Test crop: the test crop for the experiment was Cabbage (*Brassica oleracea* var. capitata)

Fertilizer application rate and time: Fertilizer was applied at the rate of 200 kgN/ha, and it was applied 2 weeks before transplanting and top dressed at the 8th week after transplanting.

Planting spacing cabbage seedlings were spaced 0.6 m between rows and 0.30 m between seedlings, 0.05 m deep, making a total of sixteen seedlings per bed.

Planting period: nursery, September 2016;field trial: October- December 2016.

Cultural practices: Weeds were controlled manually. Plots were irrigated as needed. Insects and rodents were controlled five weeks after transplanting using neem oil at a rate of 10ml of neem oil to 1litre of water.

Harvesting: The crop was harvested 13 weeks after transplanting.

Data collection: Four plants per bed were tagged and selected as representative samples; the number of leaves and head diameter were measured and used in

yield estimations. Plants were harvested from the roots, and their fresh weights were taken. Dry weights were determined after drying the plant materials at 70°C in a forced air oven for 72 hours.

Soil Analysis: Effects of the Compost on the physical and chemical properties of the soil were determined by collecting soil samples from different portions of the field before planting and after harvest. The soil samples before planting were mixed to form a composite sample, which was air-dried and taken to the laboratory for physical and chemical analyses. The soil samples were subjected to routine analysis using standard procedures (Okalebo *et al.*, 1993).

Statistical Analysis: analysis of variance (ANOVA) was used to analyse the data collected on the morphological parameters and yield of the cabbage. The analysis was carried out using Genstat Discovery Edition 4. Significant means were separated using Fisher's least significant difference at 5% probability as outlined by Obi (2002).

RESULTS

The result in Table 1 indicates the nitrogen, phosphorus, and potassium content of the compost used in the study. The nitrogen content of the compost was 18.0 g/kg, phosphorus was 19.3 g/kg, and potassium was 21.0 g/kg.

Pre- cropping physical and chemical analysis of the soil used

The result in Table 2 indicates the physical and chemical properties of the soil before application of soil amendment (brewery waste-based compost). The textural class of the soil is loamy sand soil with a pH of 7.1; total organic carbon, nitrogen, and calcium were 10.5 g/kg, 0.8 g/kg, and 2.1 cmol/kg, respectively. The total phosphorus level is moderate at 17 mg/kg. The potassium is moderate at (0.5 cmol/kg).

Effect of composts on the number of leaves of cabbage

The effect of Ibadan brewery waste-based compost (IBWBC) on the number of leaves is shown in Table 3.The number of leaves increased with the age of the plant and reduced as the head began to form. The IBWBC had the highest number of leaves for week 2, 4, 6, 8, and 10 after transplanting (4.3, 8.0, 13.8, 16.0, and 18.8, respectively), while the control had the least (3.0, 4.1, 8.2, 10.0, and 10.4). Control had the highest mean at week 12 (15.9) and was not significantly different from IBWBC (14.5).

Effect of composts on the head diameter of cabbage

Table 4 shows the effect of organic fertilizers on the head diameter of cabbage. IBWBC had the highest mean for head diameter across the production period; IBWBC (37.0 cm) wasnot significantly higher than control in week 12 (31.6 cm).

Effect of composts on the weight of the whole plant, root, and shoot of cabbage

The effect of Ibadan brewery waste-based composts (IBWBC) on the plant, root, and shoot weight of cabbage is shown in Table5. IBWBC had the highest mean plant weight (308.8 g/plant), root weight (20.9 g/plant), and shoot weight (287.9 g/plant) of cabbage and was significantly higher than the control (82.1 g/plant, 7.1 g/plant, 72.3 g/plant),respectively.

Table 1: Composition of Ibadan Brewery Wastes-Based Composts (IBWBC)

Nutrient (Total) (g/kg)	IBWBC
Nitrogen	18.0
Phosphorus	19.3
Potassium	21.0

Legend
IBWBC-Ibadan Brewery Waste Based Compost

Table 2: Pre-cropping chemical and physical analysis of soil used

Parameter	Measured value
pH (H ₂ O1:1)	7.1
OC (g/kg)	10.5
N (g/kg)	0.8
(mg/kg) P	17

	WEEKS AFTER TRANSPLANTING				
TREATMENT	9	10	11	12	13
IBWBC	16.1a	31.0a	40.4a	37.0ab	22.1a
CONTROL	8.6b	16.1b	24.1b	31.6b	12.0b

TREATMENT	Plant weight	Root weight	Shoot weight
	(g/plant)		
IBWBC	309.0a	20.9a	287.9a
CONTROL	82.1b	7.1b	72.3b

The effect of the compost on the soil after planting is shown in Table 6. The pH of the soil after cropping for all treatments has a mean of 7.1; the treatments left the soil at the neutral zone. The treatment increased the organic carbon of the soil, invariably increasing the organic matter of the soil. The brewery waste-based composts had higher values for total nitrogen, Phosphorus and potassium (1.68, 25, and 1.6, respectively), which are greater than the critical levels of the nutrients. The textural class remains loamy sand soil.

Table 4: Effect of composts on head diameter (cm) of cabbage.

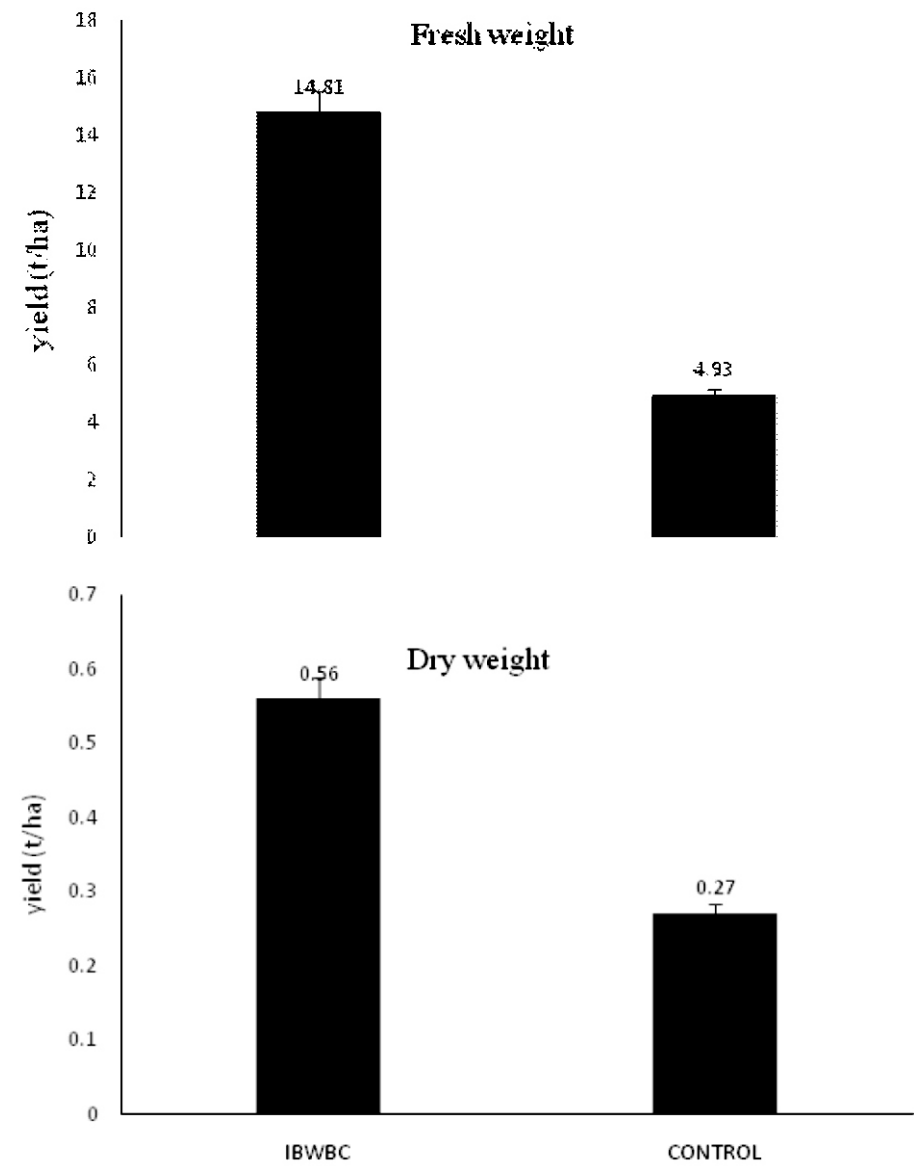


Figure 1: Effect of compost on fresh and dry fruit yield o cabbage

Table 6: Post- cropping chemical and physical analysis of the experimental soil

Parameters	IBWBC	CONTROL	Critical levels
pH (H ₂ O) 1:1	7.2	7.0	5.5- 6.5
O.C (g/ kg)	12.11	1.89	4.0-10.0
N (g/kg)	1.68	0.28	0.6-1.0
(mg/ kg) P	25	4	7.0-20.0
Cations (Cmol/kg)			
Ca	3.2	1.8	5-10
Mg	0.5	0.3	1-3
K	1.6	0.5	0.31-0.6
Na	1.2	2.2	0.3-0.8
Micronutrients (mg/kg)			
Mn	53	15	
Cu	29	25	
Fe	3	2	
Zn	8	2	1.0-5.0
Particle size analysis (g/ kg)			
Sand	856	858	
Silt	96	94	
Clay	48	48	
Soil texture (USDA)			
	Loamy Sand soil	Loamy Sand soil	

DISCUSSIONS

The use of compost in crop production not only has the potential to improve food security but can also enhance environmental sanitation (Aina and Adedipe, 1992). Waste disposal has become a significant cost factor and an important aspect in the running of a brewery operation (Fillaudeau *et al.*, 2006), with spent grain being the major waste. Ebido *et al* (2024) revealed that Brewery waste-based compost has improved the yield of amaranth when compared to the control. The

application of IBWBC increased the number of leaves of cabbage, and this is likethe report of Atta-Poku *et al.* (2014) that there was a significant increase in the number of leaves of cabbage grown with organic fertilizers. Also, the IBWBC increased the head diameter of cabbage, which is in alignment with Gamal *et al.* (2009) that N-fertilizer tends to increase the head diameter of cabbage. The compost treatment gave three times the yield obtained from the control. This confirms the work of Maheshbabu *et al.* (2007) that organic

materials act as nutrient reservoirs and, upon decomposition, are released slowly during the entire growth periods leading to higher seed yield and yield components. The compost treatment maintained the soil at the neutral zone; observation that the organic residues generally increased soil pH compared with the control is in tandem with the reports of previous workers (Opala *et al.*, 2012, and Kolawole, 2016). The composts had a significant increase in the organic carbon of the soil. The application of compost was observed to increase the organic matter; this may be due to the high amount of organic matter present in the organic materials (Bayu *et al.*, 2005). The result also showed that the application of compost had significant effect on the nitrogen content of the soil as the compost increased the total nitrogen of the soil This may be due to supply of N in the compost through mineralization associated with improved soil condition for microbial activities as a result of increased organic matter, This is in line with Adenawoola and Adejoro, (2005) who

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reported that organic residues increased the nitrogen content of the soil with time.

IBWBC had a significant increase on the potassium content of the soil after cropping. This agrees with the report of Urkurkar *et al.*(2010) that organic input increases the available potassium in the soil. The increase of soil organic matter resulted in a decrease in K fixation and subsequently increased K availability (Singh *et al.*, 2002).

CONCLUSION AND RECOMMENDATION

In conclusion, the results obtained revealed that Ibadan Brewery Waste-Based Compost had a significant increase in the Physical and chemical properties of soil, growth, and yield of cabbage compared to the control. Brewery waste-based compost could be used successfully as a soil amendment to increase yield of cabbage, as well as maintaining a good soil fertility status for sustainable organic crop production.

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RESPONSE OF COMMON BEANS (*Phaseolus vulgaris*L.) TO ORGANIC FERTILIZERS IN A MAIZE - BEANS INTERCROPPING SYSTEM IN FARMERS' FIELDS OF WESTERN KENYA.

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Abstract

Soil degradation resulting in unhealthy soils is negatively affecting food production and crop yields in western Kenya. Agroecologically based crop production practices, such as using organic fertilizers, provide a means for enhancing the soil fertility and improving crop yields of such degraded soils. A study, codesigned and managed by farmers, was conducted in the farmers' fields to evaluate the response of intercropped common beans (*Phaseolus vulgaris* L.) to organic fertilizers. The experiments were set up in four farmers' fields in different locations in *Vihiga and Kakamega* Counties using a local beans variety (*Haraka mtoka*) intercropped with maize (*Zea mays* L.). Four treatments, three organic fertilizers, namely, bokashi, biostimulant, and compost, and a control (zero) where no fertilizer was added, were replicated three times and arranged in a randomized complete block design. Crop growth (plant height, number of leaves, and leaf size) and yield of beans were determined. The growth and yield of beans were significantly affected by organic fertilizers and experimental sites. Organic fertilizers generally resulted in better growth and yield of beans with average increments in beans yield ranging from 58% to 153% compared to unfertilized plots. We conclude that organic fertilizers enhanced the growth and yield of beans, but overall soil health conditions moderated their effects. Superior soil conditions associated with long-term use of organic fertilizer resulted in better growth and yield at Ekwanda, while inferior soil attributes caused the poorer performance at Ebunangwe. Organic fertilizers may buffer soil fertility such that even without their addition in the current season, beans crop can sufficiently grow and produce a good yield, as noted for Ekwanda.

Key words: Beans (*Phaseolus vulgaris* L.); Farmers' fields; Organic fertilizers; Western Kenya

Résumé

La dégradation des sols, qui les rend impropres à la culture, affecte négativement la production alimentaire et les rendements agricoles dans l'ouest du Kenya. Les pratiques agricoles agroécologiques, telles que l'utilisation d'engrais organiques, permettent d'améliorer la fertilité des sols dégradés et d'accroître les rendements. Une étude, conçue et gérée conjointement par les agriculteurs, a été menée sur leurs parcelles afin d'évaluer la réponse du haricot commun (*Phaseolus vulgaris* L.) cultivé en association avec des engrais organiques. Les essais ont été mis en place sur quatre parcelles agricoles situées dans différentes localités des comtés de Vihiga et de Kakamega, avec une variété locale de haricot (*Haraka mtoka*) cultivée en association avec du maïs (*Zea mays* L.). Quatre traitements, trois engrais organiques (bokashi, biostimulant et compost) et un témoin (sans engrais), ont été appliqués, répétés trois fois selon un dispositif en blocs aléatoires complets. La croissance des cultures (hauteur des plants, nombre et taille des feuilles) et le rendement du haricot ont été mesurés. La croissance et le rendement des haricots ont été significativement influencés par les engrais organiques et les sites expérimentaux. Les engrais organiques ont généralement permis une meilleure croissance et un meilleur rendement, les performances les plus élevées et les rendements les plus faibles étant observés à Ekwanda et Ebunangwe. Nous concluons que les engrais organiques ont amélioré la croissance et le rendement des haricots, mais que l'état général du sol a modéré leurs effets. À Ekwanda, les conditions pédologiques optimales, associées à une utilisation prolongée d'engrais organiques, ont permis une meilleure croissance et un meilleur rendement, tandis qu'à Ebunangwe, les caractéristiques pédologiques inférieures ont entraîné des performances moindres. Les engrais organiques semblent maintenir la fertilité du sol, permettant ainsi aux cultures de haricots de se développer et de produire un bon rendement, même sans leur apport durant la saison en cours, comme observé à Ekwanda.

Mots-clés: Haricots (*Phaseolus vulgaris* L.); Champs agricoles; Engrais organiques; Ouest du Kenya

Introduction

The common beans (*Phaseolus vulgaris* L.) are among the most important grain legumes and is cultivated in over 34 million hectares of land globally (FAO, 2023). It is nutritionally rich being a major source of quality protein of up to 23.5% (high in the essential amino acids of leucine, phenylalanine, and lysine), complex carbohydrates at 59 - 66%, group B vitamins, minerals (including calcium, potassium, phosphorus, magnesium, iron and zinc) giving 4% ash, dietary fibre (4.05%) and phenolics (Neupane *et al.*, 2024; Vidak *et al.*, 2023). Beans also play significant environmental roles through biological N-fixation that enhances soil fertility and by controlling pests and diseases under multiple cropping systems with minimal use of synthetic fertilizers and pesticides (Vidak *et al.*, 2023). In Kenya, common beans is fundamental to the local

diet, serving as the primary source of protein, particularly to the low-income populations who cannot afford costly animal proteins. Its high lysine, which is generally low in maize, cassava, and rice, the main staple cereals in Kenya, makes beans a great complement to these cereals in the country and partly justifies the common practice of intercropping beans with maize nationally. Beans are also a major source of income for the Kenyan farmers from local markets as well as export markets, especially as French beans. Land and particularly soil degradation is however, limiting the yields of crops, including beans in Kenya. Kirui *et al.* (2021) reported western Kenya as a hot spot for land degradation in the country, resulting in crop yield reductions as high as 75% (Ajwera *et al.*, 2024). The leading aspects of soil degradation, especially among the smallholder farmers in western Kenya, is

nutrient mining associated with continuous cultivation and nutrient losses caused by erosion, leaching, and the removal of crop residues from crop fields (Ajwera *et al.*, 2024). There is a need, therefore, for curtailing further soil degradation and rehabilitating the degraded soils.

Agroecological crop production systems, such as the application of organic fertilizers, are potential means to check soil degradation and improve the productivity of the soils in western Kenya. When obtained from the farm (crop residues and animal wastes), organic fertilizers facilitate on-farm recycling with relatively low fertilization costs compared to synthetic fertilizers. Besides nutrient addition to soils, application of organic fertilizers also enhances physical, chemical, and biological soil properties, including soil porosity, soil permeability to water, and soil nutrient-holding capacity (Abdulraheem *et al.*, 2023; Avery, 2021). Organic fertilizers increase soil organic matter (SOM) that feeds soil microbes, retains soil nutrients and water, and binds soil particles to form stable aggregates (Li *et al.*, 2017) thus improving soil structure. In addition, organic fertilizers slowly release nutrients to plants a process that may restrict their leaching losses (Panday *et al.*, 2024).

The slow nutrient release by organic fertilizers, as well as low and variable nutrient contents, can be limitations to crop production (Panday *et al.*, 2024). The low nutrient content of organic fertilizers dictates that large quantities of bulky organic fertilizers are required to meet the crop nutrient needs, acquisition and handling of which may be costly if sourced away from the farm. The variability in nutrient content makes accurate application difficult, while the slow release of nutrients risks causing nutrient deficiency, particularly at peak nutrient demands, consequently reducing yield (Panday *et al.*, 2024). The type, amount, and timing of application of organic fertilizers are therefore bound to influence soil nutrient availability and crop yield (Larkin, 2020) with possible different effects of

different fertilizers. Furthermore, nutrient release from organic fertilizers is largely via the microbial decomposition of the organic material, releasing simpler nutrients readily available to plants, a process that is affected by the soil conditions and soil microbial activities. This makes it important to establish the effects of the various organic fertilizers on crops at specific sites and under specific cropping systems. A study was therefore codesigned and managed by smallholder farmers to evaluate the response of common beans to three organic fertilizers in a common beans-maize intercropping system on four farmers' fields for two seasons (March to May and August to October) of 2025

MATERIALS AND METHODS

Study sites

The experiment was set up in four farmers' fields, two in Kakamega County (Emakunda and Emalindi villages), and two in Vihiga County (Ebungangwe and Ekwanda villages). The Kakamega sites, have an average annual temperature of 21 °C and a bimodally distributed rainfall averaging 1800-2200mm annually. Emalindi is at 0°13'13.44" N and 34°61'65.68" E, and an altitude of 1481m above sea level. The soils are well-drained red-loamy soils. Emakunda is at 0°13'24.45" N and 34°63' 89.24" E and an altitude of 1500m above sea level. The soils are reddish-brown sandy clay luvisols. Ekwanda and Ebungangwe, in Vihiga County, have a mean annual temperature of 23 °C, with bimodally distributed rainfall averaging 1500-2000mm annually. Ebungangwe is located at 0°0'44.8" N and 34°34'15.1" E, at an altitude of 1554m above sea level and characterized by sandy clay reddish-brown luvisols soil. Ekwanda is at 0°5'32.9" and 34°40'6.7" E, at an altitude of 1498m above sea level with reddish-brown clayey soils.

Organic-fertilizer preparation

a) Bokashi

Bokashi, a nutrient-rich soil fertilizer made by fermenting organic matter, was prepared in layers. Each layer consisted of about 40kg of dry chopped crop residue mixed with the same quantities of topsoil and decomposed manure (in the ratio of 1:1:1). To this mixture, a litre of yeast/molasses/tap water mixture was added. The yeast /molasses/ water mixture was made by suspending 100g of yeast in a mixture of 2 litres of molasses and 5 litres of tap water. Thereafter, about 9kg each of wheat bran and charcoal dust, 3 kg of wood ash, 0.35 kg of sand, and 30 g of crushed bones were added to complete the layer. The layer was allowed to settle for 24 hours before the pile was turned twice daily for the first 3 days and then once daily for the subsequent 11 days to thoroughly mix the ingredients. The fertilizer was ready for use by day 14. A sack of 6 kg of the ready bokashi fertilizer was then soaked in a 20-liter bucket of water for 10 days, being shaken twice daily to obtain the liquified extract for foliar application.

b) Bio-stimulant

Solid bio-stimulant fertilizer balls were prepared from fresh cow dung, topsoil, beans flour, molasses, and water. For every 25 kg of fresh dung, about 2.5 kg of topsoil, 0.5 kg of beans flour, and 1liter of molasses were added. These were then mixed, and water added as the mixture was moulded into balls of uniform texture and size (fistful). The balls were then dried in the shade while being turned daily till they were well dried and ready for use. For its foliar spray (liquid bio-stimulant fertilizer), 10kg of the freshly prepared mixture was put in a sack before being moulded into balls and then hung in a container with 40litres of water. The sack was shaken at least twice daily while stirring the water it was immersed in for a period of five days for the resultant extract to be ready for use.

c) Compost

Compost fertilizer was made by decomposing organic materials. Wood chippings (sawdust), green crop residue, dry crop residue, and animal manure were mixed in the ratio of 3:2:1:1 by weight and then piled in an enclosed, well-ventilated area in the order of wood chippings at the bottom, then animal manure, green crop residue, and finally dry crop residue at the top. Topsoil, enough to form a thin layer on top of the pile, was added, and some water sprinkled to make the pile moist but not wet. The layering was repeated in a vertical arrangement until the pile was about 1M high, after which it was covered with banana leaves and allowed to settle for a week. Thereafter, the pile was regularly turned to mix the ingredients therein at a 3-day interval in the first two weeks while moistening. The turning interval was then reduced to once a week for the subsequent four weeks. The fertilizer was ready for use when all its constituent materials were fully broken down, and it was now crumbly.

Its liquid form for foliar application was obtained from vermicompost. At an elevated composting structure, animal manure was added, then red worms (*Eisenia fetida*) were introduced, and then biodegradable kitchen refuse was added. The structure was then covered to create a dark environment for the ideal operation of the worms. The liquid extract was collected into a container placed beneath the structure. The worms were continuously fed by adding kitchen refuse as liquid vermicompost was being collected.

Crop establishment and management

A local variety of common beans (*Phaseolus vulgaris* L.), "Haraka mtoka," was intercropped with a local composite maize (*Zea mays* L.) variety. The crops were planted between 19th and 22nd March 2025 (onset of the long rains) and from 18th to 23rd August 2025 (onset of the short rains). The experimental plots measured 3m x 2m with the maize planted at a spacing of 80cm x 25cm. Two rows of beans spaced at 40cm x

10cm were planted between two rows of maize, with the rows of beans at 20 cm from the rows of maize. The organic fertilizers were applied at planting at basal rates (about 100g per hill for bokashi and compost, and one fistful ball for bio-stimulant) and later as foliar feeds to the point of runoff at five weeks after planting (5WAP). For foliar application, the liquid extracts of bokashi, bio-stimulant, and vermicompost were diluted at 1:15 (extract: water).

Experimental Design and Treatments

The experiment consisted of four treatments (organic fertilizers): (i) bokashi, (ii) compost, (iii) bio-stimulant, and (iv) zero (a control without fertilizers). At each site, the experimental units were arranged in a randomized complete block design with three replicates.

Measured parameters

Soil and organic fertilizer analysis.

The baseline status of the soils in the fields and the organic fertilizers applied were analysed for chemical properties and textural classification (for soil). Soils were sampled in a zigzag manner across the plots to a depth of 30cm. From each site, a composite soil sample was prepared and subjected to chemical and textural analyses. Organic fertilizers were prepared in bulk at a central place, and representative samples of each was chemically analysed for pH, EC, and the major macro nutrients.

Plant growth and yields

At the start of the season and before the commencement of data collection, four common beans plants in the net plots (two centre rows) were randomly selected and tagged for data collection. All data were collected only from the tagged plants. Plant height, number of leaves, and size of leaves were measured at an interval of 2 weeks from the 2nd week after planting (2WAP). The length of the central leaflet of the recently produced fully expanded trifoliate leaf of beans plants was measured and used to estimate the leaf size of the trifoliate leaf using the equation of Pohlmann et al. (2021):

$LA=1.092L^{1.946}$

Where LA is the leaf area; L is the length of the central leaflet of the trifoliate leaf. The beans were harvested at physiological maturity (after the 8th week after planting), and the grains were dried to a moisture content of 14% before being weighed to obtain the yield.

Data Analysis

The data for plant height, number of leaves, leaf size, and yield per plot were subjected to analysis of variance (ANOVA) and significant means separated using Fisher's least significant difference (LSD) using SAS software (SAS Institute Inc., 2004).

RESULTS

Soil characteristics and the organic fertilizers:

Soil properties differed significantly across the sites. Where as the other experimental sites had clay-textural soils, Eburnangwe, had sandy clay loam texture (Table 1). The pH of the soils at the study sites were highly to slightly acidic, with the lowest pH (4.91 - highly acidic) in Emakunda and the highest (5.91 - slightly acidic) in Ekwanda. Ekwanda exhibited better soil fertility as reflected in higher cation exchange capacity (CEC), organic matter, and exchangeable bases than Eburnangwe. Regarding history of using of organic fertilizers, Eburnangwe site was largely using organic fertilizers and agroecology-related cropping practices for the first time whereas, Ekwanda site had used organic fertilizers for over four years. Emakunda and Emalindi sites were categorized as intermediate between Eburnangwe and Ekwandain terms of using organic fertilizers. Among the organic fertilizers, bokashi had a lower pH (close to neutral) and carbon to nitrogen ratio (C:N). The biostimulant had relatively higher pH (more alkaline), electrical conductivity (EC), percent carbon, and percent potassium than the others.

Plant height, number of leaves, and leaf size

Plant height and number of leaves increased gradually across the study sites and organic fertilizers from week 2 to week 8 (Fig. 1, 2). The plant heights in Eburnangwe, Emalindi, and Emakundain significantly differed between weeks 2 and 4 but significantly differed between weeks 4 and 6. On the contrary, plant heights at weeks 2, 4, and 6 were significantly different in Ekwanda. In all the sites and across the organic fertilizers applied, the increment in height from week 6 to 8 was insignificant. The number of leaves, however, declined insignificantly in Eburnangwe and Emalindi but significantly in Ekwanda between week 6 and week 8.

Apart from Ekwanda where the leaf size tended to increase from week 2 through to week 8, in the other sites, leaf size decreased from week 2 to week 4, then increased from week 4 to week 6 before declining from week 6 to week 8 (Fig. 3). The size of leaves at weeks 2 and 4 were significantly lower than those at week 6 in Eburnangwe, Emalindi and Emakunda across all the organic fertilizers. Eburnangwe had the lowest leaf sizes in weeks 2 and 4, which were significantly lower than those in the other sites. Ekwanda had significantly higher leaf size in week 4 than the other sites, which was comparable to the highest leaf sizes (week 6) in the other sites. Leaf size peaked at week 6 for all sites and all organic fertilizers.

The plots without organic fertilizers (zero) had significantly shorter plants at week 8 and lower leaf size than those with organic fertilizers in Eburnangwe and Emakunda, and lower than the Bokashi plot in Emalindi. Organic fertilizer application did not significantly affect plant height and size of leaves in Ekwanda, nor did it affect the number of leaves across the sites.

Yield of beans

Across the sites, organic fertilizers significantly increased the yield of beans compared to zero plots

(Fig. 4). The increment in beans yields due to organic fertilizers averaged 58%, 85%, 107% and 153% at Ekwanda, Eburnangwe, Emalindi, and Emakunda sites, respectively.. The zero plot at Ekwanda had significantly higher yields than the zero plots at all the other sites and higher than all the organic fertilizers at Eburnangwe. On the overall, Eburnangwe had a lower yield per plot of beans, which was significantly lower than that of Ekwanda.

DISCUSSION

The four study sites showed clear differences in soil physical and chemical properties (Table 1). Eburnangwe, a sandy clay loam soil with a short agroecological management history, had the lowest organic matter content, CEC, and exchangeable base levels, indicating limited nutrient- and water-holding capacity. Its moderately acidic soil reaction is likely to exacerbate nutrient leaching and reduce overall fertility. Ekwanda, a clay soil with a long agroecological history, exhibited the highest CEC, relatively higher pH, and substantially greater concentrations of exchangeable Ca, Mg, and K. These properties indicate a more buffered and fertile soil with greater capacity to retain nutrients. Emalindi and Emakunda, both clay soils with intermediate agroecological management histories, had higher organic matter and total nitrogen contents than Eburnangwe but lower available phosphorus. Emakunda was the most acidic site, a condition likely to further constrain phosphorus availability. These site differences highlight the importance of site-specific soil fertility management.

The three organic fertilizers exhibited distinct chemical characteristics (Table 2) with important implications for soil fertility management. Bokashi, characterized by a near-neutral pH, low EC, and low C:N ratio, is likely to provide rapid nutrient mineralization and early crop nutrition. The bio-stimulant showed high alkalinity, salinity, carbon content, and potassium concentration, indicating strong soil-amending potential but also a higher risk of salinity and nutrient

imbalance if improperly applied. Compost exhibited moderate pH, low salinity, higher nitrogen content, and a wide C:N ratio, suggesting a primary role in long-

term soil organic matter accumulation and gradual nutrient release.

Table1: Soil characteristics of the experimental sites at the beginning of the study

Site	Sand (g/kg)	Silt (g/kg)	Clay (g/kg)	T/Class	Agroecological history	pH (H ₂ O)	CEC (cmol/kg)	OM (g/kg)	C (g/kg)	N (g/kg)	P (mg/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)
Ebunangwe	669	118	213	loam	New	5.2	4.9	18.5	10.3	0.9	10	0.1	1.5	0.8
Ekwanda	249	238	513	Clay	Old	5.9	13.2	26.7	15.5	1.4	16	0.3	7.9	1.9
Emalindi	389	118	493	Clay	Intermediate	5.3	10.6	37.4	21.7	1.8	2	0.2	4.0	1.8
Emakunda	329	178	493	Clay	Intermediate	4.9	8.8	37.7	21.9	1.8	5	0.2	2.6	1.0

Table 2: Chemical properties of the organic fertilizers used in the study.

Organic fertilizer	pH 1:2 (H ₂ O)	EC(ms/cm)	OC (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	C:N
Bokashi	7.8	3.45	11.30	1.17	0.16	0.82	0.71	0.27	9:60
Bio stimulant	9.3	15.50	34.60	1.50	0.26	2.33	0.80	0.33	19:10
Compost	8.5	3.85	13.10	2.16	0.13	0.15	0.70	0.29	21:70

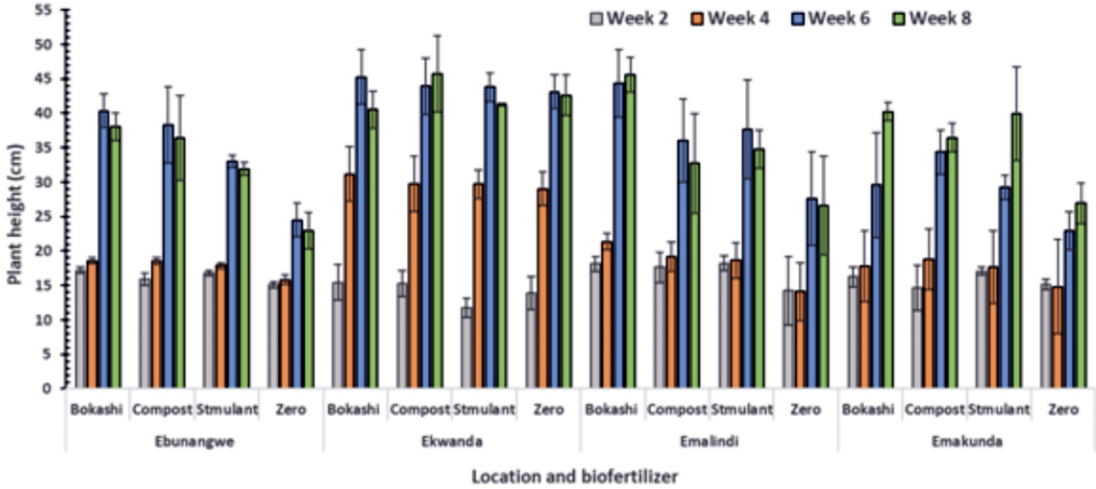


Fig.1. Plant height (cm) across the study sites for the different organic fertilizers from week 2 to week 8.

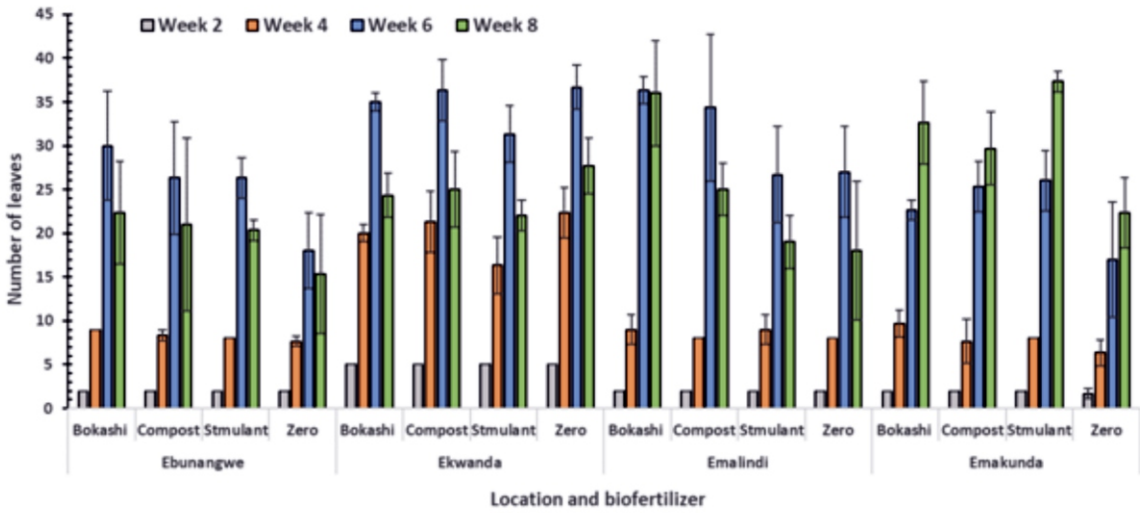


Fig.2: Number of leaves across the study sites and organic fertilizers from week 2 to week 8.

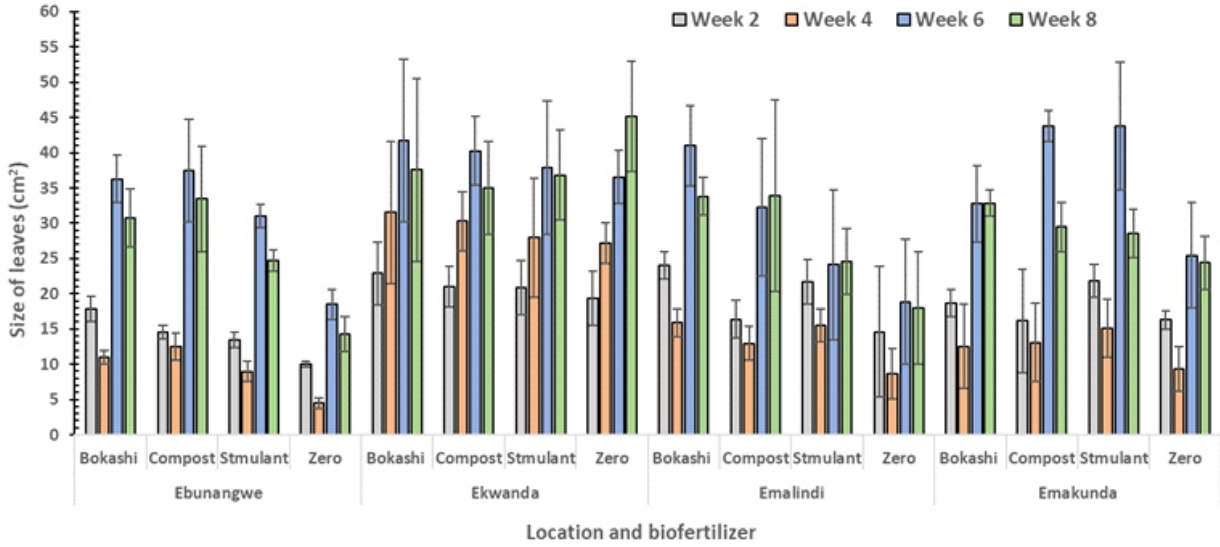


Fig. 3: Size of leaves across the study sites and organic fertilizers from week 2 to week 8.

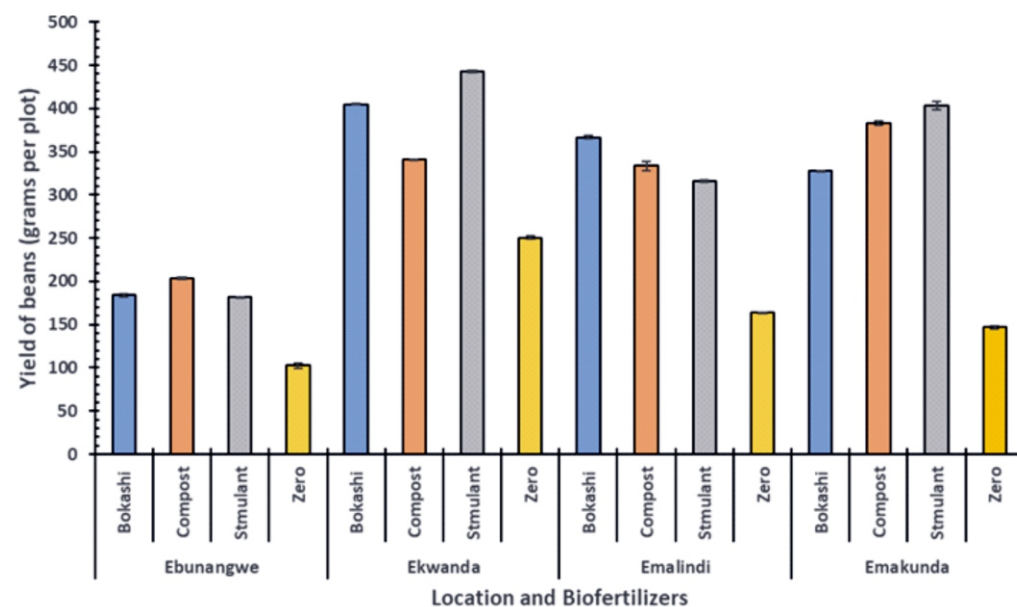


Fig. 4: Yield of beans (weight at 14% Moisture content) per plot across the study sites and organic fertilizers.

Plant height, number of leaves, and leaf size gradually increased from week 2 to week 8, with rather limited increments between weeks 2 and 4 at Ebunangwe, Emalindi, and Emakunda (Fig. 1, 2, 3). However, in Ekwanda, the plant height and number of leaves increased significantly over the weeks. Plant height, number of leaves, and leaf sizes at week 4 in Ekwanda were much higher than those of the other sites and comparable to those at week 6 of these other sites. This points to better crop performance in Ekwanda than the other sites, which is also evident from the higher yield of beans. We attribute the higher crop growth and yield at Ekwanda to its superior chemical properties (Table 1), resulting from prolonged application of organic fertilizers, and the poor growth and yield of beans at Ebunangwe to its limited nutrients and water-holding capacity.

Organic fertilizers are known to slowly release nutrients to crop plants (Panday et al., 2024; Vasileva et al., 2025) through microbial decomposition, resulting in possible nutrient limitations and consequently reduced development, especially at the early stages of the crops (Vasileva et al., 2025). Such suppression of development is bound to be more pronounced in crops growing under limited nutrients due to low amounts of nutrients released or a mismatch between the nutrients released and those demanded by the crops. This could account for the poorer initial growth of beans in Ebunangwe, Emalindi and Emakunda. The generally poor soil health at Ebunangwe, as reflected in its sandiness, low organic matter and CEC, and low macronutrients, including N, P, and K was possibly responsible for its lower crop performance at the initial crop stages and ultimately lower yield per plot relative to Ekwanda.

To the contrary, beans at the Ekwanda site attained higher and nearly maximum plant height, leaf number, and leaf sizes by the 4th week compared to the other sites. By attaining higher leaf sizes and numbers by week 4, the crops at the Ekwanda site possibly had a longer duration of greater photosynthesis, leading to more food made in the life span of the crop that consequently accounted for the observed higher yields. In beans, longer leaf area duration that extends the photosynthetic period is known to be more related to higher overall yields than the maximum leaf area achieved (Trindade et al., 2010).

In areas that have accumulated organic matter from long-term applications of organic fertilizers, such as the Ekwanda site, continuous decomposition of organic matter releases and retains nutrients in the soil (Bot and Benites, 2005) thus ensuring a sufficient supply of nutrients to crop plants even when no fertilizers are currently applied. Indeed, even the unfertilized plots at Ekwanda had comparable and better growth and yield of beans than fertilized plots at the other sites. The superior performance of the Ekwanda site relative to the other sites reflects the cumulative benefits of long-term organic matter accumulation, which enhances nutrient retention and buffering capacity.

Organic fertilizers generally increased plant height, number of leaves, and leaf sizes compared to the plots where no fertilizer was added in Ebunangwe and Emakunda (Fig. 1, 2, 3) and yield per plot across all the sites (Fig. 4). This is attributed to the ability of organic fertilizers to not only provide nutrients (Abdulraheem et al., 2023; Avery, 2021) but to also improve soil structure especially of degraded soils and consequently enhance soil nutrients and water retention (Abdulraheem et al., 2023; Larkin, 2020; Li et al., 2017) thus supporting the growth and yield of crops. This is consistent to previously reported increase in growth and yields of beans due to organic fertilizers (Ali et al., 2023). However, responses to organic fertilizers were moderated by baseline soil fertility,

emphasizing the need for site-specific nutrient management strategies in agroecological systems.

CONCLUSIONS

Organic fertilizers enhanced the growth and yield of beans in the maize-beans intercropping systems under smallholder conditions in western Kenya. The magnitude of the response was strongly influenced by site-specific soil properties and history of use of organic fertilizers. Sites with relatively long history of use of organic fertilizers and that had higher organic matter and CEC exhibited greater and more stable productivity, including in unfertilized plots, indicating soil fertility buffering effects. These findings underscore the importance of sustained soil organic matter restoration and context-specific organic nutrient strategies for improving resilience and productivity of smallholder agroecosystems.

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**Application Rates of Poultry Manure and Seed Size
Effects on The Growth and Yield of Fluted Pumpkin
(Telfairia occidentalis Hook F.)**

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Abstract

Fluted pumpkin (*Telfairia occidentalis* Hook F.) is economically important and a nutritionally dense leafy green vegetable in West Africa, valued for its protein-rich seeds and edible leaves. Productivity in farmers' fields, however, remains low because of poor soil fertility, inadequate knowledge and application of agronomic practices, as well as limited access to fertilizers. This study, therefore, evaluated the effects of poultry manure (PM) application and the size of seed on the growth and yield of *T. occidentalis* under humid tropical conditions. The study was conducted at the University of Uyo Teaching and Research Farm during the 2011 early cropping season, using a 3 × 4 factorial experiments arranged in a Randomized Complete Block Design (RCBD). Treatments comprised three seed sizes from small (<14 g), medium (14-20 g), to large (>20 g); and four rates of PM (0, 5, 10, and 15 t ha⁻¹), replicated three times. From the results, PM significantly ($P \leq 0.05$) improved vine length, number of leaves, tendrils, and foliar yield, with PM at 5 t ha⁻¹ producing the highest values. Similarly, pod number, stem girth, and total foliar yield increased with increasing PM rates, attaining a maximum of 13.15 t ha⁻¹ at 15 t ha⁻¹ PM. Seed size significantly influenced early vegetative growth, as large seeds produced more vigorous seedlings and higher leaf biomass, but had no significant effect on pod yield. The interactive effect between Poultry manure application rate and seed size was not significant, showing independent treatment effects. Overall, the application of 15 t ha⁻¹ poultry manure is recommended to enhance soil fertility, growth, and yield of *T. occidentalis* under sandy loam conditions. Adoption of this practice offers a sustainable, low-cost pathway to boost productivity among smallholder farmers.

Keywords: Fluted pumpkin, leafy greens, seed technology, yield



Résumé

La courgecannelée (Telfairia occidentalis Hook F.) est un légume-feuille vert à haute valeur nutritive et économiquement important en Afrique de l'Ouest, apprécié pour sesgraines riches enprotéines et sesfeuilles comestibles. Cependant, sa productivité reste faible en raison de la faible fertilité des sols, de connaissances et d'applications agronomiques insuffisantes, ainsi que d'un accès limité aux engrais. Cette étude a donc évalué les effets de l'application de fumier de volaille et de la taille des graines sur la croissance et le rendement de T. occidentalis en conditions tropicales humides. L'étude a été menée à la ferme d'enseignement et de recherche de l'Université d'Uyo au début de la saison de culture 2011, selon un dispositif expérimental factoriel 3 × 4 en blocs aléatoires complets (BAAC). Les traitements comprenaient trois tailles de graines : petites (< 14 g), moyennes (14-20 g) et grandes (> 20 g) ; et quatre doses de fumier de volaille (0, 5, 10 et 15 t ha⁻¹), répétées trois fois. D'après les résultats, l'application de fumier de volaille (FV) a significativement amélioré (P < 0,05) la longueur des tiges, le nombre de feuilles, de vrilles et le rendement foliaire, les valeurs les plus élevées étant obtenues avec une dose de 5 t ha⁻¹ de FV. De même, le nombre de gousses, la circonférence des tiges et le rendement foliaire total ont augmenté avec la dose de FV, atteignant un maximum de 13,15 t ha⁻¹ à 15 t ha⁻¹ de FV. La taille des graines a influencé significativement la croissance végétative précoce : les grosses graines ont produit des plantules plus vigoureuses et une biomasse foliaire plus importante, mais n'ont pas eu d'effet significatif sur le rendement en gousses. L'interaction entre la dose de fumier de volaille et la taille des graines n'était pas significative, ce qui indique des effets indépendants des traitements. En conclusion, l'application de 15 t ha⁻¹ de fumier de volaille est recommandée pour améliorer la fertilité des sols, la croissance et le rendement de *Triticum occidentalis* en conditions de sol sablo-limoneux. L'adoption de cette pratique offreune solution durable et économique pour accroître la productivité des petits exploitantsagricoles.

Mots-clés: Courgecannelée, légumes-feuilles, technologie des semences, rendement

Introduction

Fluted pumpkin (*Telfairia occidentalis* Hook F.), known in local Nigerian parlance as Ugwu, Ikong Ubong, or Apiroko, is important in West African cuisine and agriculture. This perennial, dioecious vine, of the Cucurbitaceae family, is prized not only for its highly nutritious leafy greens but also for its protein- and oil-rich edible seeds. While traditionally cultivated across the humid lowland tropics of Nigeria, Ghana, and Sierra Leone, its potential for addressing food and nutritional security is gaining renewed scientific and commercial interest (Adewumi and Adebayo, 2023). The exact origin of fluted pumpkin is debated, but a strong consensus identifies it as indigenous to West Africa. Nwonuala and Akani (2022) report that it is widely believed that wild populations have been

largely replaced by cultivated forms, making it a true domesticate of the region. Fluted pumpkin is a vigorous climber, able to reach lengths of over 20 meters in branched tendrils. It is dioecious, meaning individual plants are either male or female. Female plants are typically more robust, with larger leaves and longer vegetative periods, making them more desirable for leaf harvest (Obiagwu and Madukwe, 2021). The large, fluted pods are a distinctive feature, measuring up to 70 cm long and containing 40-110 flat, oily seeds. A significant challenge in its cultivation is the recalcitrant (desiccation-sensitive) nature of its seeds, which lose viability rapidly if not planted soon after extraction from the pod, posing a constraint on seed storage and distribution (Eze *et al.*, 2020).

Fluted pumpkin is adaptable but thrives in deep, well-drained, loamy soils rich in organic matter, with a slightly acidic to neutral pH (5.5-6.5). It requires a warm, humid climate with annual rainfall between 1,000mm and 2,500mm. Although moderately drought-tolerant, consistent soil moisture is crucial for high leaf yield, and irrigation can enable year-round production (Akinrotimi *et al.*, 2021). Cultivation is primarily from seeds, sown on mounds, ridges, or beds. Close spacing is used for intensive leaf production, while wider spacing with staking is preferred for fruit and seed development. Smallholder farmers often intercrop it with staples like yams and cassava, where it serves a dual purpose as a food source and a soil cover for weed suppression (Okon *et al.*, 2022).

The economic and nutritional importance of fluted pumpkin cannot be overstated. The leaves are a rich source of protein, vitamins (A, C, and E), minerals (iron, calcium, magnesium), and antioxidants. Recent analyses confirm that the leaves contain significant amounts of iron and folate, making them a potent dietary tool in combating anaemia, a prevalent public health issue (Airadion *et al.*, 2020). The seeds are exceptionally nutritious, containing up to 30% protein and 50-60% high-quality oil, rich in essential fatty acids. This oil has potential applications in the food and cosmetic industries (Olaniran *et al.*, 2023).

Beyond its nutritional value, fluted pumpkin holds profound medicinal importance in ethnobotanical practices. Extracts from the leaves and seeds have demonstrated anti-anemic, anti-inflammatory, anti-diabetic, and hepatoprotective properties in scientific studies, validating their traditional uses (Ejike *et al.*, 2021). The plant also contributes to rural livelihoods; it is a significant income source, particularly for women who often dominate its marketing. Its cultivation in home gardens enhances household dietary diversity and provides a safety net against food insecurity (Nwachukwu and Otekunrin, 2024). Despite its importance, the commercial production of fluted

pumpkin remains suboptimal. The sector is dominated by resource-poor smallholder farmers who face numerous challenges. In addition, and notably, inherently low soil fertility, particularly in the heavily weathered soils of the Niger Delta, and the high cost and limited access to inorganic fertilizers (Chukwuka and Uka, 2022). Furthermore, the recalcitrant nature of seeds and a lack of improved, high-yielding cultivars constrain productivity.

These challenges create a significant gap between domestic supply and the soaring demand driven by rapid urbanization and population growth. Consequently, prices often become prohibitive, especially during the off-season, forcing consumers to seek less nutritious alternatives (Adewumi and Adebayo, 2023). This scenario underscores the urgent need for research into sustainable agronomic practices that can boost yield and make cultivation more profitable and resilient.

A promising strategy to overcome production constraints lies in the integrated use of organic soil amendments and improved planting material. The frequent and often inefficient use of mineral fertilizers is not only expensive but also associated with environmental pollution, such as soil acidification and water eutrophication. In contrast, organic manures like poultry manure offer a sustainable alternative. Poultry manure is rich in nitrogen, phosphorus, potassium, and micronutrients. Its application improves soil structure, enhances water-holding capacity, and promotes beneficial microbial activity, leading to sustained nutrient release (Ojo *et al.*, 2023). Studies on other indigenous vegetables have consistently shown that poultry manure application significantly improves vegetative growth, leaf yield, and overall plant health. Simultaneously, the selection of high-quality planting material is a critical factor often overlooked by traditional farmers. Seed size is a key physiological attribute that can influence germination vigour, seedling establishment, and subsequent crop

performance. Larger seeds typically contain greater food reserves, which can support the young seedling until it can photosynthesize independently. While some studies on crops like cowpea and maize have confirmed a positive correlation between seed size and seedling vigour, research specific to fluted pumpkin has yielded conflicting results, indicating a knowledge gap that needs to be addressed (Nwonuala and Akani, 2022). There is a clear, synergistic opportunity to investigate the combined effects of poultry manure application and seed size selection on the productivity of fluted pumpkin. Understanding this interaction can provide a low-cost, accessible, and sustainable protocol for smallholder farmers to enhance their yields. By optimizing these two factors, farmers can potentially reduce their reliance on chemical inputs, improve germination rates, and achieve more robust plant growth for both leaf and seed production. Therefore, this study was designed to generate knowledge to bridge the existing production gap. The study therefore determined the effect of different application rates of poultry manure and the size of seeds on the growth and yield of fluted pumpkin (Telfairia occidentalis).

Materials and method

Description of the Study Area and Experimental Procedures

The experiment was conducted during the 2020 early cropping season at the University of Uyo Teaching and Research Farm, Use-Offot, Uyo, Akwa Ibom State, Nigeria. Uyo lies within the humid tropical rainforest zone of southern Nigeria, between latitudes 5.18°-5.28°N and longitudes 7.26°-7.57°E, at an elevation of approximately 38 m above sea level. The region experiences wet and dry seasons, with mean annual rainfall ranging between 268.8 and 270.1 mm, mean monthly relative humidity of about 80%, and mean monthly temperature of 26.8-27.0°C. The site, previously fallowed for one year to restore fertility, had

been used for growing cassava, maize, fluted pumpkin, yams, and garden egg. Experimental design and field layout followed a 3 × 4 factorial arrangement in Randomized Complete Block Design (RCBD), of three seed size categories; viz small (<14 g), medium (14-20 g), and large (>20 g) and four poultry manure (PM) levels: 0, 5, 10, and 15 t/ha. This yielded 12 treatment combinations replicated three times, giving 36 plots in total. Each plot measured 3.0 m × 2.5 m, separated by 1 m paths, with a total experimental area of 850 m². Poultry manure was incorporated two weeks before planting. Soil and manure analysis were carried out using composite soil samples collected at 0-15 cm and 15-30 cm depths for physical and chemical analysis. Parameters determined included pH (1:2.5 soil-water suspension), total nitrogen (Micro-Kjeldahl), available phosphorus (Bray P-1), exchangeable cations (Ca, Mg, K, Na), and particle size distribution (hydrometer method). The soil was classified as sandy loam. Poultry manure samples were oven-dried at 60-80°C, sieved through a 2 mm mesh, and analysed for N, P, K, Ca, Mg, Zn, Fe, Cu, and Mn. Seeds were sourced from Afaha market (IbesikpoAsutan LGA, Akwa Ibom State, Nigeria), air-cured for two days, and planted on July 18, 2020, at 4-5 cm with 80 × 60 cm spacing, two seeds per hole. Major weeds included *Ipomea involucrata*, *Axonopus compressus*, and *Chromolaena odorata*, and these were manually controlled at 5 and 11 weeks after planting (WAP). Chlorpyrifos (1 mL per 4 L of water) was used for the control of pest infestations by termites, grasshoppers, and caterpillars. Data was collected from four central plants per plot tagged for weekly observations at 3, 6, 9, and 12 WAP. Growth parameters measured included vine length, number of leaves and tendrils, and foliar yield. Yield components recorded were the number of pods per plot, the length of pods, pod girth, and pod yield. Data were analysed for Analysis of Variance (ANOVA), and post-hoc test using Fisher's Least Significant Difference (FLSD) at 5% probability level (Gomez and Gomez, 1984).

Results and Discussion

The baseline physico-chemical characteristics of the experimental soil are presented in Table 1. The soil was classified as sandy loam, with a high sand fraction (75.60%) and lower silt (10.40%) and clay (14.00%) contents. This textural class typically promotes good drainage and aeration (Brady and Weil, 2008), which is beneficial for root development and prevents waterlogging. However, such soils are also known for their moderate to low inherent nutrient-holding capacity, making them susceptible to nutrient leaching. The soil was slightly alkaline (pH 8.00 in H⁺O), a condition that can influence the availability of essential micronutrients. The electrical conductivity was low (5.80 DS/m), indicating that salinity was not a constraint to plant growth. Notably, the soil exhibited moderately high levels of organic carbon (4.05%), total nitrogen (2.86%), and available phosphorus (45.33 mg/kg). This suggests a pre-existing moderate fertility status. The exchangeable bases were dominated by calcium (4.80 cmol/kg) and magnesium (1.40 cmol/kg), while potassium (0.17 cmol/kg) was relatively low. The combination of a sandy loam texture and a potentially low potassium level underscore the likelihood that the soil would be responsive to organic amendments, such as poultry manure, which can improve cation exchange capacity and supplement essential nutrients.

The application of poultry manure (PM) significantly (P ? 0.05) enhanced all measured growth attributes of Telfairia occidentalis at six weeks after planting (Table 2). Vine length, number of leaves, number of tendrils, and foliar yield exhibited a consistent, positive response to increasing PM rates. The application of 15 t/ha PM resulted in the most pronounced growth, producing the longest vines (91.06 cm), the highest number of leaves (36.45), and the greatest foliar yield (10.13 kg). This represents a substantial improvement over the control, clearly demonstrating the role of PM in mitigating the limitations of the sandy loam soil. The

growth promotion observed can be attributed to the synergistic effects of PM. Poultry manure is a rich source of organic matter and nutrients, particularly nitrogen, which is crucial for vigorous vegetative growth and chlorophyll synthesis (Adekiya *et al.*, 2020). Its application improves soil structure, enhances microbial activity, and facilitates a slow, sustained release of nutrients, thereby matching the crop's demand and reducing losses through leaching which is a critical factor in sandy soils.

Concerning seed size, large seeds produced significantly taller vines (81.48 cm), more leaves (37.61), and higher foliar yield (12.13 kg) compared to medium and small seeds. This is consistent with the principle that larger seeds possess greater food reserves, providing more energy and resources for seedling emergence and early establishment (Milberg *et al.*, 2000). A key finding from this study is the non-significant (NS) interaction between poultry manure and seed size (PM × S) for all growth parameters. This indicates that the effects of PM application and seed size were independent and additive. In other words, the positive effect of using large seeds was consistent across all manure rates, and conversely, the benefit of applying PM was evident regardless of the seed size used. This suggests that the advantage conferred by larger seed reserves is not diminished by nutrient availability from manure, and both factors can be managed separately to optimize growth.

The positive effects of PM application extended to the yield components of T. occidentalis (Table 3). Pod number, pod length, pod girth, and total pod yield all increased significantly with higher rates of PM application. The highest pod yield (13.15 t/ha), along with the longest (69.09 cm) and widest pods (59.08 cm), was recorded at the 15 t/ha PM rate, while the control plots yielded the lowest (5.88 t/ha). This robust response underscores the importance of adequate nutrition, particularly during the reproductive and pod-filling stages. The nutrient-rich environment provided

by the high PM rate likely supported better flower formation, fruit set, and photosynthate allocation to the developing pods.

In contrast to the clear effects on vegetative growth, seed size had only a slight and non-significant influence on yield components. Although plots with large seeds recorded a marginally higher pod yield (13.60 t/ha), the differences were not statistically significant. This indicates that while seed size is a critical factor for initial vegetative vigour, its influence on ultimate yield may be superseded by post-emergence agronomic practices, particularly nutrient management, as the plant develops.

Again, the interaction between PM and seed size (PM × S) was not significant for any yield parameter. This reinforces the conclusion that the rate of poultry manure application is a far more dominant factor determining the yield of *T. occidentalis* than the size of the seed planted. The absence of interaction simplifies agronomic recommendations, as the benefits of optimal manure application can be realized irrespective of the seed size category used by farmers.

Table 1: Soil physical and chemical properties of the experimental site before planting and poultry manure

Soil Parameter	Soil depth	Poultry	Value(%)
	0-15	manure	
pH(H ₂ O)1:2	5.2	pH (H ₂ O) 1:1	8.0
	5.8	pH (CaCl ₂)	6.2
EC (DS/M)	0.065		
Organic Matter (g/kg	1.09	Total P	0.94
Total N (g/kg)	2.90	Nitrogen	2.86
Available P (mg kg ⁻¹)	45	Calcium	6

Summary and Conclusion

In summary, the results of this study demonstrate that the application of poultry manure is a highly effective strategy for enhancing both the growth and yield of *Telfairia occidentalis* cultivated on a sandy loam soil. The significant improvements in vegetative growth and pod yield with increasing PM rates up to 15 t/ha highlight the role of organic amendment in improving soil fertility and plant nutrition. While large seeds provided an advantage for early seedling growth, this effect was independent of manure application and did not translate into a significant yield advantage. The consistent lack of significant interaction between the two factors indicates that their effects are additive. Therefore, under the described soil and climatic conditions, the application of 15 t/ha poultry manure is recommended as the optimal practice for maximizing the productivity of *T. occidentalis*.

Exchangeable Bases(cmol/kg)		Magnesium	1.88
Ca	4.8	Potassium	0.5
Mg	1.4	Sodium	0.1
Na	0.1	Organic carbon	4.05
K	0.2	C/N Ratio	4:2
Acidity	2.8		
ECEC	9.3		
Base Saturation	69.79		
Particle Size Analysis(g/kg)			
Sand	756.00		
Silt	104.00		
Clay	140.00		
Textural Class	Sandy		
	Loamy		

Table 2: Effects of poultry manure (PM) and seed size on growth attributes of *Telfairia occidentalis* at 6 weeks after planting

Treatment	Vine length (cm)	Number of leaves	Number of tendrils	Foliar yield (kg)
Seed size				
Small	65.56	32.96	3.51	8.75
Medium	79.83	36.23	3.80	10.76
Large	81.48	37.61	3.95	12.13
LSD	2.38	1.67	NS	1.33

(P=0.05)

Poultry

Manure

0	46.42	20.19	2.18	3.01
5	60.14	32.27	3.08	5.78
10	74.80	35.81	3.28	9.16
15	91.06	36.45	3.63	10.12
LSD	17.33	4.21	1.11	3.02

(P=0.05)

PM x S	NS	NS	NS	NS
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NS: Not significant

Table 3: Effects of poultry manure (PM) and seed size on number of pods per plant, length of pod (cm), girth of pod(cm), and yield(t/ha) of *Telfairia occidentalis*

Treatment	Number of pods/plots	Length of pods (cm)	Girth of pod (cm)	Pod yield (t ha ⁻¹)
Seed size				
Small	5.25	64.71	56.86	12.75
Medium	5.40	68.84	58.12	13.33
Large	5.50	70.70	58.45	13.60
LSD	NS	NS	NS	NS
(P=0.05)				
Poultry				

(*Telfairia occidentalis* Hook F.)

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Manure

0	4.11	45.51	43.31	5.88
5	5.12	60.33	51.40	8.35
10	5.18	65.19	55.40	12.30
15	5.89	69.09	59.08	13.15
LSD	NS	6.62	4.21	2.72

(P=0.05)

PM x S	NS	NS	NS	NS
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The Role of Biochar in Agricultural Production; Soil Fertility and Water Quality Improvement: An Overview

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ABSTRACT

A review of the roles of biochar in agricultural production highlights its relevance in combining water treatment and soil enhancement, which ultimately leads to higher crop yield and carbon sequestration over time. The demand for biochar as a soil amendment, its efficacy in improving water quality for sustainable agriculture, and addressing the negative effects of climate change cannot be undermined. Biochar is a porous, largely carbon-based material produced through pyrolysis, a thermochemical process that occurs in the absence or low oxygen. The biomass used for biochar could be obtained from plant and animal residue or waste. Biochar performance is dependent on the type of feedstock and the pyrolysis conditions employed during its production.

The global demand for biochar is rising for various uses, including fertilizer materials, as it ameliorates nutrient deficiency in nutrient-depleted soil because of continuous cropping, excessive synthetic fertilizer application, and other human activities. Biochar, an environmentally friendly soil conditioners, is suggested for large-scale field application due to its numerous benefits, which are adsorbent for removal of contaminant/inorganic pollutants from water, purifying water, carbon sequestration, soil fertility improvement, nutrient release and uptake, soil water retention, crop yield improvement, and enhances fertilizer use efficiency thereby reducing greenhouse gas emissions as a results of its unique characteristics like high surface area and pore volume.

This review focuses on the potential of biochar as an agricultural amendment that enhances water quality, soil fertility, and crop productivity, in addition to serving as a growth medium and composting material. Composting of biochar produced from various organic sources can ensure the stability of the soil, restoration of marginalized soil, and reduce carbon emissions associated with agriculture.

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In conclusion, this review revealed that biochar can also serve as media for growing vegetables in a screen house, which enhances the growth of high-value food crops, especially fruits and vegetables, to meet the increasing global demand for food by humans.

Keywords: Biochar, Soil Fertility, Water Quality, Crop Productivity, Carbon Sequestration

RÉSUMÉ

Une analyse du rôle du biochar dans la production agricole met en lumière son importance pour le traitement de l'eau et l'amélioration des sols, ce qui permet d'accroître les rendements agricoles et la séquestration du carbone à long terme. L'intérêt du biochar comme amendement du sol, son efficacité pour améliorer la qualité de l'eau et favoriser une agriculture durable, ainsi que sa capacité à atténuer les effets néfastes du changement climatique, sont indéniables. Le biochar est un matériau poreux, principalement composé de carbone, produit par pyrolyse, un procédé thermochimique qui se déroule en l'absence ou en faible quantité d'oxygène. La biomasse utilisée pour sa production peut provenir de résidus ou de déchets végétaux et animaux. Les performances du biochar dépendent du type de matière première et des conditions de pyrolyse mises en œuvre lors de sa production. La demande mondiale de biochar est en hausse pour diverses applications, notamment comme engrais. Il permet en effet de pallier les carences en nutriments des sols appauvris par la monoculture intensive, l'utilisation excessive d'engrais de synthèse et d'autres activités humaines. Le biochar, un amendement de sol écologique, est recommandé pour une application à grande échelle en raison de ses nombreux avantages : adsorption des contaminants et polluants inorganiques présents dans l'eau, purification de l'eau, séquestration du carbone, amélioration de la fertilité des sols, libération et absorption des nutriments, rétention d'eau, amélioration des rendements agricoles et optimisation de l'efficacité des engrais. Grâce à ses caractéristiques uniques, telles qu'une surface spécifique et un volume poreux élevés, il contribue à réduire les émissions de gaz à effet de serre. Cette étude se concentre sur le potentiel du biochar comme amendement agricole. Il améliore la qualité de l'eau, la fertilité des sols et la productivité des cultures, tout en servant de substrat de culture et de matériau de compostage. Le compostage du biochar issu de diverses sources organiques peut garantir la stabilité des sols, la restauration des sols marginalisés et la réduction des émissions de carbone liées à l'agriculture. En conclusion, cette étude révèle que le biochar peut également servir de substrat pour la culture de légumes sous serre, favorisant ainsi la croissance de cultures vivrières à haute valeur ajoutée, notamment les fruits et légumes, afin de répondre à la demande alimentaire mondiale croissante.

Mots-clés: Biochar, fertilité des sols, qualité de l'eau, productivité des cultures, séquestration du carbone

Introduction

Rapid global population growth has increased demand for grains and other food materials, thereby placing growing pressure on agricultural systems worldwide. This makes farmers use uncontrolled synthetic fertilizers and chemical inputs to increase crop production (Rathore *et al.*, 2021). The consequences may include soil compaction, reduced soil fertility, air and water pollution, and greenhouse gas emissions

(Tripathi *et al.*, 2020). The utilization of agricultural waste to produce biochar could solve the disposal and management of agricultural waste. Biochar is a carbon-rich material obtained by heating biomass in the absence of air (Panwar *et al.*, 2020). The type and composition of the feedstock, particle size, reaction temperature, heating rate, and reactor parameters all affect the efficiency of biochar formation from biomass. Unique physical and chemical characteristics

of biochar, like large surface area, high pore volume, high cation exchange capacity, and functional groups, make it suitable for a wide range of applications (Leng *et al.*, 2021). The applications of biochar impact soil characteristics, soil texture, and greenhouse gas emission control (Sri Shalin *et al.*, 2020). Multiple nutrient inadequacies related to severe soil nutrient deficiency have emerged as the most significant global constraint to agriculture's long-term productivity (Singh *et al.*, 2022).

Biochar is known to achieve several sustainability goals, including C sequestration, soil and plant growth improvements, and energy production (Marris 2006). Biochar production yields several beneficial co-products like hydrogen, bio-oil, syngas, process heat, and liquid smoke via the pyrolysis process, while the implication of small stoves for food processing in developing countries could help to reduce respiratory diseases and decrease the pressure on forests (Barrow 2011, Mankasingh *et al.*, 2011).

Recently, biochar has been used as an additive for composting and soil remediation to control greenhouse gases and NH₃, humidification, and to inactivate heavy and organic pollutants. The incorporation of compost and biochar as soil amendments is affordable and long-lasting, with a positive impact on soil enhancement and the growth of plants (Guo *et al.*, 2020).

Descriptions and Characteristics of Biochar

Biochar is known to have a low bulk density due to its porous structure, leading to a high specific surface area ranging from 50 - 900 m² g⁻¹ (Schimmelpfennig and Glaser, 2012), and a high-water retention capacity (Glaser *et al.*, 2002). From a chemical point of view, the most striking feature of biochar is its polycondensed aromatic structure (Glaser *et al.*, 1998) caused by dehydration during thermochemical conversion (Schimmelpfennig and Glaser, 2012), leading to its black colour. This structure is also responsible for its

relative recalcitrance compared to other organic matter in the environment. In addition, basic ash compartments lead to a high pH value. Several studies show that the quality of the feedstock and production conditions, such as pyrolytic temperature and time, have a significant influence on the quantity, quality, and elemental compositions of the biochar (Dume *et al.*, 2015). Therefore, the selection of suitable feedstock and optimum pyrolytic protocol is crucial for biochar producers to produce a designer biochar amendment that is made to improve a specific nutrient deficiency in soil in agriculture. Low temperature biochar has high volatile matter content, but lower fixed carbon and ash contents than the high temperature biochar (Bourke *et al.*, 2007).

Biochar Production Method

A variety of thermal conversion processes can be used to prepare biochar (Deal *et al.*, 2012). Pyrolysis systems employed to process unused and excess crop and agroforestry residues for biochar production can be categorized into four types: (i) slow pyrolysis, (ii) fast pyrolysis, (iii) flash pyrolysis, and (iv) gasification. Slow pyrolysis performed under lower temperature (<400-500°C) and with long contact times often results in a high yield of biochar (35%) (Meyer and Quicker, 2011). Faster pyrolysis or gasification operates at higher temperatures (<800°C) and gives a high yield of combustible gases in relation to the solid biochar (12%) (Laird *et al.*, 2009). The most employed method is slow pyrolysis. This process involves direct thermochemical decomposition (exothermic reaction) to transform low-density residue matrix into a biochar at a temperature range of 450-500°C under low-toxic or anoxic conditions in a closed reactor (Gul *et al.*, 2015). Biochar can be produced at scales ranging from large industrial facilities down to the individual farm and even at the domestic level through a distributed network of small facilities that are located close to the crop residue source.

Biochar Production Process

Biochar production from agricultural residue starts with biomass feeding into the combustion chamber in the absence of air. There are mainly five production stages: drying, conditioning, torrefaction, exothermic pyrolysis, and endothermic pyrolysis at different temperatures. As the temperature rose to 150-180 °C, the biomass conditioning process began, releasing carbon dioxide. The biomass breakdown starts during the torrefaction phase at 180-250 °C, producing carbon dioxide and carbon monoxide. When an exothermic reaction begins at about 250 - 400 °C, it produces a significant quantity of heat, and condensable vapours such as water, acetic acid, methanol, acetone, etc., and tar are the prevailing products when the temperature rises to 400 °C. When the temperature rises above 450 °C, it is possible to convert biomass to biochar. The biochar production process is practically completed, but biochar contains considerable amounts of tar. To avoid this further, increase the temperature up to 500°C to complete the carbonization stage (Panwar *et al.*, 2020)

Effects and Contribution of Biochar Application to Soil and Crop Yield

Many studies and reviews have pointed out the potential advantages of biochar application as a soil amendment (Sohi *et al.*, 2010), having benefits beyond carbon sequestration. The benefits are: improvement of soil physical properties that benefit crops (Ajayi and Horn, 2016), improved retention and availability of soil nutrients (Dume *et al.*, 2016), improved biological activity, by providing metabolizable organic carbon substrates (Hersztek *et al.*, 2016) and consequently higher crop yields and societal advantages through mitigation of climate change by carbon sequestration (Zhang *et al.*, 2017). Biochar production and application to soil enhances the rate of soil carbon sequestration through a shift from the short-term bio-

atmospheric carbon cycle to the long-term geological carbon cycle (Lehmann *et al.*, 2011)

I. Effects of Biochar Application on Soil Fertility

Biochar efficiently sequesters adequate amounts of carbon in soil over time, thus increasing soil fertility and crop productivity, thereby mitigating climate change because of deforestation, urbanization, and industrialization (Semida *et al.*, 2019). Various parameters, such as feedstock type, pyrolysis chamber temperature, soil type, and biotic interactions, were discovered to influence the efficiency of biochar application in agricultural soil. Biochar has the capacity to absorb carbon and reduce greenhouse gas emissions in the soil (Ashiq *et al.*, 2020).

Tanure *et al.* (2019) applied the biochar to a maize crop with two particle sizes (2.0-0.5 and <0.5 mm) at six doses (0, 5, 10, 20, 40, and 60 g/kg) under two soil moisture conditions in a greenhouse environment. It was found that biochar boosted the photosynthesis process, stomata conductance, moisture retention, pore ratio, reduced bulk density, and fertility when added to soil (Tanure *et al.*, 2019). Biochar enhances soil pH and lowers the exchangeable acidity because of its high magnesium and calcium content (Kannan *et al.*, 2021) Cation exchange capacity (CEC) is essential for soil quality, and adding biochar to the soil increases CEC. A higher CEC of soil indicates a high capability for nitrogen fixation, which is crucial for plant growth. Biochar can affect soil microbes in terms of pH, pore structure, surface area, sorption behaviour, and nutrient content (Zhang *et al.*, 2021). According to recent studies, biochar's growth-promoting effects on soil microbes have been verified.

Biochar can also improve plant nutrition and yield since it is the source of nutrient elements such as nitrogen (N), phosphorus (P), potassium (K), and other

trace elements (Purakayastha *et al.*, 2019). In an ecological farming system, biochar increased crop yield by 25% in tropical soils. Mensah and Frimpong (2018) reported that biochar addition in two soil types of significantly increased biomass and yield of maize. Moreover, adding biochar to soil, with or without chemical fertilizer, has been reported to supply sufficient macro- and micro-nutrients to plants (Piash *et al.*, 2021).

II. Effect of Biochar Application on Crop Productivity

Several researchers have reported that biochar applications to soils have shown positive responses for net primary crop production, grain yield, and dry matter. The rice yield was increased between 8.5% - 10.7% when the application rate of rice straw biochar was about 4.5 t/ha (Liu *et al.*, 2016). Furthermore, applying the same biochar in greenhouses at the rates of 10, 25, and 50 t/ha increased the rice and wheat yields by 12% and 17%, respectively (Wang *et al.*, 2012).

III. Climate Change Mitigation

Biochar has the potential to reduce the negative effects of climate change because the inherent fixed carbon in raw biomass that would otherwise degrade to greenhouse gases is sequestered in soil for years. Recently, the use of surplus organic matter to create biochar has yielded promising results in the sequestration of carbon. Lehmann *et al.* (2006) estimated that a potential global carbon sequestration of 0.16 Gt yr⁻¹ can be obtained from biochar production from forestry and agricultural wastes. In India, biochar from residues of maize, castor, cotton, and pigeon pea can sequester about 4.6 Mt of total carbon annually in soil, making it a carbon sequestering process (Venkatesh *et al.*, 2015). Several studies have reported on environmental benefits of biochar incorporation which will reduce emission of non-CO₂ greenhouse gases by soil (Zwieten *et al.*, 2010) that

could be due to inhibition of either stage of nitrification and/ or inhibition of denitrification, or promotion of the reduction of N₂O; increases CH₄ uptake from soil and long-term carbon sequestration in soil (Srinivasa *et al.*, 2013).

IV. Effect of Biochar Application to Soil Microbial Activity

Biochar serves as a suitable habitat for a large and diverse group of soil microorganisms (bacteria, fungi, algae, protozoa, etc.) A higher retention of microorganisms in biochar-amended soils may be responsible for greater activity and diversity due to a high surface area, as well as surface hydrophobicity of both the microorganisms and biochar. Carbonized biomass, such as rice husk charcoal or wood ash, has been a valuable material as a soil amendment. The optimal biochar combining fertilizer and carbon storage function in soils would activate the microbial community, leading to nutrient release (Venkatesh *et al.*, 2018). Applied biochar may provide habitats for the growth of soil-dwelling microorganisms (Tong *et al.*, 2014) and protect them against natural enemies.

V. Nutrient use efficiency

Biochar significantly increases the efficiency and reduces the need for synthetic fertilizer application to the soil with sustainable crop yields. The incorporation of biochar into soil alters important soil chemical qualities, such as soil pH increasing towards neutral values, and typically increases soil cation exchange capacity. Glaser *et al.* (2002) observed an increasing trend of bioavailable P and base cations in biochar-applied soils. Biochar application boosts the soil fertility and improves soil quality by raising soil pH, increasing moisture retention capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity, and retaining nutrients in soil (Lehmann *et al.*, 2006). For agronomic purposes, biochar applied with N fertilizer helps to counter the potentially unavailable biochar N (Steiner *et al.*, 2008).

VI. Application of Biochar as Growing Media

Conventional farming has a few disadvantages, including high water and land requirements, high use of pesticides, soil degradation, and nutrient runoff (Reganold and Wachter, 2016). When comparing hydroponics to conventional agriculture, the former is preferred because of its ability to sustainably meet future food demands. When comparing vertical farming to conventional agriculture, the former is preferred because of its ability to sustainably meet future food demands as a result of the increasing human population. Many researchers suggest that biochar has similar physicochemical characteristics to other growing media (such as peat and coir) and enhances high-value crop production. (Barrett *et al.*, 2016). There is a constant search for new materials with more suitable properties for plant growth. The use of biochar to replace peat (Tian *et al.*, 2012) and vermiculite substrate in growing media improves nutrient retention and is also disease and drought resistant. In addition, Dunlop *et al.* (2015) suggested that biochar be used as a

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medium for hydroponic systems, enhancing high-value food crops' growth.

Conclusions

In recent years, more attention has been drawn to the use of biochar in agricultural production based on scientific evidence that points to the effectiveness of biochar as useful material for reclamation of degraded agricultural soil and mitigating greenhouse gas emissions, the use of biochar has emerged as an environmentally friendly strategy, biochar has the capacity to provide solution to agricultural issues such as land degradation due to acidity, salinity, and nutrient depletion. However, the agricultural advantages of biochar are solely dependent on using specific biochar at the optimal field application rate under suitable soil types and parameters. Biochar can improve soil as a growing medium to meet the ever-increasing food demand and generate additional income by improving crop productivity and providing other revenue opportunities, leading to economic and agricultural benefits.

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