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The feminization of sustainability: Gender dynamics, digital innovation, and agricultural policy in developing nations

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ABSTRACT

Sustainable farming in developing countries encounters systemic obstacles that go beyond technological advancements, including financial limitations, environmental stressors, and deep-rooted gender disparities. This paper promotes the idea of the feminization of sustainability, contending that women's empowerment serves as a fundamental factor for ecological efficiency rather than an ancillary social objective. Utilizing comparative data from Asia and Sub-Saharan Africa (SSA), the research integrates literature on funding shortages, technological disparities, and gendered resource access to illustrate how these factors interact in influencing agricultural resilience. Case studies demonstrate that secure land tenure, gender-sensitive funding, and accessible digital infrastructure promote both productivity and fairness. The examination underscores Weather-Forecast-Based Advisory Services (WFBAS) as a scalable resource for climate adaptation, while stressing that the implementation of Agriculture 4.0 technologies necessitates favourable legal and financial conditions. The study finds that incorporating gender equity into financial and technological structures is essential for establishing sustainable agrifood systems.

KEY WORDS

Food security; Gender equality; Agricultural finance; Digital transformation

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Introduction

The adoption of the 2030 Agenda for Sustainable Development has recognized sustainable agriculture as a fundamental pillar in ensuring food security and economic stability globally [1]. In developing countries, where agriculture provides more than three-fourths of the labor force and contributes significantly to the Gross Domestic Product, agricultural sustainability is crucial for national survival [2]. However, productivity is increasingly compromised by the "twin shocks" of climate change and rapid globalization [3]. Recent literature emphasises that this crisis is exacerbated by natural resource depletion and deteriorating local ecology, which often leaves agricultural output in regions like SSA and South Asia (SA) far below its potential [4,5]. Consequently, a fundamental paradigm shift is required moving from resource-intensive, "weather-blind" production towards ecologically sound systems that prioritise long-term resilience over short-term yields [6,7].

While the transition towards "Agriculture 4.0" characterized by the integration of drones, robotics, and smart sensors offers transformative potential for resource optimization and carbon footprint reduction, its implementation is stymied by a pervasive "financing gap" [8,9]. Empirical evidence suggests that agrarian-based small-and-medium enterprises (SMEs) in emerging economies find it exceptionally difficult to obtain credit due to inflexible institutional policies and a lack of traditional collateral [10]. Furthermore, the "adverse economic geography" of rural areas characterized by vast distances and scattered populations frequently disincentivises private financial institutions from supporting sustainable entrepreneurship [11].

Crucially, this paper argues that the transition to sustainability is not merely a technical challenge but a social one, deeply rooted in gender dynamics. There is no doubt that although women comprise nearly half of the agricultural workforce, they remain systematically marginalized in terms of land ownership, credit access, and decision-making [12,13].

Essentially, the central hypothesis of this paper is to investigate the greater role women have to play in sustainable agricultural transformation, particularly in the developing countries. In doing this, the study adopts an analytical, literature-based approach to explore gender dynamics, financing, and digital innovation in sustainable agriculture. It synthesises secondary data from peer-reviewed journals, FAO, World Bank, and IFAD reports between 2000 and 2025, focusing on developing countries, especially in Asia and SSA, where agriculture is vital and gender disparities are significant. The selected sources address three themes: the agriculture financing gap, the digital divide in adopting Agriculture 4.0 technologies, and gender empowerment's role in sustainability. The paper examines countries like India and Kenya, linking financing constraints to technological adoption through a gender equity lens, highlighting regional challenges and success stories of gender-responsive policies.

Why the Future of Sustainable Farming is Female (and High-Tech)

Agriculture is undergoing a significant demographic shift, often referred to as the feminization of agriculture. Here, we view feminization of sustainability as a conceptual lens to embed gender equity at the core of agricultural transformation. Thus, it contends that women's empowerment is a structural driver of ecological efficiency, not an optional add-on. This framework places women's roles within feminist political ecology and sustainability transitions and shows that inclusive financing, secure land rights and equitable access to digital innovation are crucial for achieving resilient agri-food systems.

As we have already mentioned, globally, women constitute nearly half of the agricultural workforce, with regional variations

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that are even more pronounced. For example, in the SA region, 71 percent of women are employed in agrifood systems compared to 47 percent of men, while in SSA, 66 percent of women's employment is in agriculture compared to 60 percent of men. Despite this growing presence, women's contributions are frequently invisible, often categorized as "unpaid family labor". This invisibility undermines both food security and ecological resilience. Significantly, studies conducted by FAO and UNDP suggest that women constitute 45 percent of the agricultural labor force in developing countries, increasing to 60 percent in parts of Africa and Asia, essential for achieving Sustainable Development Goal 2 (Zero Hunger) [14]. Nevertheless, female farmers face barriers like limited access to land and education. Studies indicate that equal resource access could boost food production by nearly 30 percent, alleviating hunger for 150 million people globally. Recent data show that the trend of land ownership has recently changes across the countries: in certain case favouring women and in others against women. However, overall, the trend is positive across the different continents. This has been shown in Figure 1.

On the other hand, communities such as the Dayak Benawan in Indonesia exemplify the importance of women's ecological knowledge. Women here act as custodians of traditional agro-ecological practices, embedding cultural and spiritual dimensions into production systems. However, the expansion of globalized, intensive agriculture has increasingly alienated them from decision-making processes, eroding indigenous knowledge critical for sustainability [15].

Women's land rights as the ultimate sustainable asset

Land ownership remains the most formidable barrier to women's empowerment in agriculture. Without secure tenure, women lack collateral for loans and incentives for long-term investment in sustainable technologies. Evidence from Upper Egypt shows that securing women's inheritance rights catalyzed income growth and educational attainment, creating a virtuous cycle of empowerment and sustainability [15]. As FAO notes, securing women's land rights is not optional but a strategic necessity for sustainable agrifood systems [14]. In Figure 1, we see certain progress towards this direction. Further Table 1 provides a detail data on this.

Table 1. Share of agricultural land owned by women across countries (2009 vs 2023).
(All figures are in percentages)

Country	2009	2023	Percentage Change	Country	2009	2023	Percentage Change
Asian Countries				**African Countries**			
Cambodia	–	52.8	–	Kenya	31.79	54.46	71
Georgia	–	27.7	–	Lesotho	33.91	–	–
India	–	11.9	–	Liberia	–	40.82	–
Indonesia	–	19.7	–	Madagascar	–	42.99	–
Kyrgyzstan	19.96	–	–	Malawi	54	57.8	7
Nepal	–	34.4	–	Mali	–	8.6	–
Oman	–	6.59	–	Mauritania	–	16.7	–
Pakistan	5.67	2.16	-62	Mozambique	50.68	38.68	-24
African Countries				Namibia	27.82	–	–
Benin	–	14.9	–	Niger	29.1	14.7	-49
Burkina Faso	17.4	17.5	1	Nigeria	24	31.6	32
Cameroon	–	25.78	–	Rwanda	50.64	45.58	-10
Chad	25.64	–	–	Senegal	–	7.6	–
Comoros	41.02	–	–	Sierra Leone	–	34.6	–
Côte d'Ivoire	–	16.2	–	Tanzania	40.1	47.9	19
DR Congo	43.43	–	–	Togo	17.16	22.7	32
Eswatini	–	56.2	–	Uganda	–	38.7	–
Ethiopia	49	50.4	3	Zambia	–	30.5	–
Gambia	–	2.8	–	Zimbabwe	-	56.4	-
Guinea-Bissau	–	24.3	–	Tanzania	40.1	47.9	19

Source: Same as Figure 1.

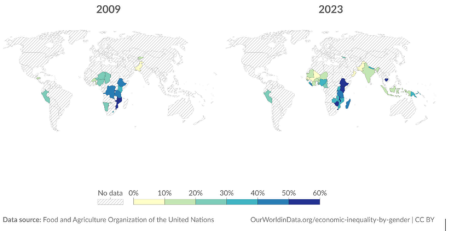

Figure 1. Share of agricultural land owned by women across countries (2009 vs 2023).
(Source: Retrieved May 23, 2026 from https://archive.ourworldindata.org/20260518-095641/grapher/share-of-agricultural-land-owners-that-are-women.html (archived on May 18, 2026).

Data shown in Table 1 indicate a notable change. Among the Asian countries, in Cambodia, women now hold more than half of the agricultural land. In Nepal also, mor than one-third of agricultural land (34.4 percent) is owned by the female. In Georgia, Indonesia and India, recent data shows ownership of agricultural land by women, though comparable historical data of these countries are not available. However, among the Asian countries, in Pakistan we show a negative trend, where the portion of agricultural land held by women has considerably decreased by over 62 percent during the reference period.

Similarly, among the African countries, significant progress in women's ownership of agricultural land is seen in Malawi and Kenya . In Malawi , approximately 58 percent of the

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agricultural land are owned by the women, indicating 7 percent increase over 2009 data. Similarly, in Kenya, over 54 percent of agricultural land are owned by the women, also revealing 71 percent increase over 2009 data. However, in this region, negative trend is seen in countries like Niger and Mozambique (49 and 24 percent respectively) marking decrease in Agricultural Land Ownership (ALO) over the reference period.

On the issue of ALO by women, there is nothing significant than to mention here the FAO Director-General QU Dongyu, who emphasized that addressing gender inequalities in agrifood systems can significantly advance efforts to eliminate poverty and hunger. It was further argued that closing gender gaps in farm productivity and wages could boost global GDP by nearly $1 trillion and decrease food insecurity for 45 million individuals[14].

Furthermore, the study also advocated that women empowerment in agriculture is not merely a social goal but a measurable driver of ecological efficiency. Essentially, it has been advocated that empowered women farmers are more likely to adopt sustainable practices, diversify plant cover, and reduce pesticide use, thereby enhancing ecological resilience [14].

In Table 2, we can see the role played by gender in the major agriculture and related activities. Certain cases of success led by Gender have also been summarized.

Table 2. Activities relating to agriculture: role of gender and success stories from developing countries.

Activity Area	Major Arguments	Role of Gender	Success Stories / Country Contexts
Food Security	Women are central to food production and nutrition, yet face systemic barriers	Women contribute up to 80% of food production in some regions but lack equal access to assets.	In Burkina Faso, women's vegetable gardens improved household nutrition and income [16,17].
Governance and Livelihoods	Inclusive governance enhances accountability and resource allocation.	Women's participation in farmer groups strengthens agency.	In India, women's self-help groups under the Swarnajayanti Gram Swarozgar Yojana improved local governance, resource distribution and poverty [18,19].
Rural Finance	Access to credit empowers women economically and socially.	Women-led microfinance strengthens empowerment.	In Uganda, women's village savings and loan associations increased investment in farming and education [20]. Similar findings were also noticed in Mozambique [21].
Land Policy and Tenure	Secure tenure is vital for investment and sustainability.	Women's inheritance rights catalyze empowerment.	In Upper Egypt, securing women's inheritance rights boosted income and education [15].
Extension Services	Traditional extension overlooks women farmers.	Participatory approaches engage women effectively.	In Kenya, Farmer Field Schools increased women's adoption of integrated pest management [22].
Agricultural Labor	Women's labor is undervalued and often unpaid.	Recognition and fair wages are essential.	In Bangladesh, recognition of women's labor in rice cultivation improved policy targeting [23].
Innovation and Technology	Technology adoption is shaped by gendered access.	Women's involvement improves outcomes.	In Bangladesh, women's participation in aquaculture innovations raised household nutrition and income [24].
Markets and Value Chains	Women face constraints in market access.	Collective action strengthens bargaining power.	In Kenya, women's dairy cooperatives increased income and decision-making authority [25,26].
Livestock	Women manage small livestock critical for nutrition.	Women-led cooperatives improve productivity.	In Ethiopia, women-led dairy cooperatives enhanced bargaining power and household welfare [27].
Fisheries and Aquaculture	Women dominate post-harvest but lack credit/training.	Participation enhances food security.	In Bangladesh, women's involvement in aquaculture projects improved food security and income [28,29].
Forestry	Women depend on forests for fuel and fodder.	Participation improves conservation.	In Nepal, women's forest user groups improved resource management and equity [30,31].
Water Management	Women are primary water collectors but excluded from governance.	Inclusion improves efficiency.	In India, women's participation in irrigation committees enhanced equity in water distribution [32,33].
Risk and Vulnerability	Women face disproportionate risks from climate change.	Community-based mechanisms enhance resilience.	In Tanzania, women's participation in climate adaptation groups improved resilience to drought [17,34].
Monitoring and Evaluation	Gender-sensitive M&E frameworks are needed.	Tools like WEAI & WELI capture empowerment.	In Ethiopia, the WEAI tool revealed significant gains in women's decision-making power in agriculture [17,35].

Source: Author's presentation.

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Note: WEAI: Women's Empowerment in Agriculture Index; WELI: Women's Empowerment in Livelihood Index

Challenges and Constraints

Ensuring sustainability of agricultural practices and policies in developing countries is accompanied by various challenges and limitations, especially on the gender front. For instance, issues like limited financial resources, infrastructure, and traditional farming practices can act as barriers to the adoption of climate-resilient and innovative farming technologies. Moreover, agricultural policies may be biased more towards productivity than sustainability, leading to issues like environmental sustainability being less addressed. For example, in a research study conducted by Gwendolen DeBoe in OECD while drawing evidences from 130 studies relating to agricultural policies and its effects on productivity and environmental sustainability has shown that agricultural policies impact the sector's performance through conflicting economic and environmental signals [36]. It was reported that coupled support harms efficiency and productivity while increasing emissions and water quality issues. On the other hand, decoupling support can positively affect the economy if designed well. Dependency on support lowers efficiency, and certain subsidies may encourage risky practices. Policy shifts can lead to land abandonment, affecting biodiversity and landscapes. Targeted agri-environmental schemes are recommended.

However, issues like gender inequality, where women are denied rights to own farmland, access credit facilities, and decision-making opportunities, can act as barriers to promoting sustainable agriculture in developing countries. Women, who are at the core of farming activities, have often been ignored in promoting and supporting sustainable agriculture, leading to increased levels of marginalization. It is only through this approach that sustainable agriculture can be made environmentally resilient and socially inclusive in developing countries.

Thus, four key issues need to be taken up for detail discussion. First, we need to have a comprehensive idea about the general obstacles to agricultural sustainability. Second, we also need to examine how to tackle climate change as a systemic constraint. Third, to fulfil the primary objective of this paper, we shall also examine the challenges that have come up owing to the recent digitalization of agriculture which has led to the emergence of Agriculture 4.0 technologies. And in this context, the related gender dimensions will also be analyzed. Finally, we shall explore the constraints faced on the financing front towards achieving Agriculture 4.0 in a gender empowered environment. The first two issues we shall take up in this section itself. And the next two we shall take up in the next sections of the paper.

General obstacles to agricultural sustainability

Presently, agricultural productivity in developing countries has faced a threat due to the exploitation of natural resources and deterioration of local ecology [4]. For instance, in developing countries like those in SSA and SA, poor soil quality and degradation have become a common problem, leading to agricultural productivity remaining far below its potential [5]. A recent study conducted by Kihara et al., found that soil degradation in SSA to the extent 65 percent of arable land is affected by nutrient depletion and erosion [37]. The study recommended that strategies like conservation agriculture and integrated soil fertility management can enhance soil health and productivity, but adoption is hampered by labor demands and lack of resources. Significantly, the study also argued to adopt site-specific digital advisory systems as a crucial mechanism for effective solutions.

Similarly, the use of non-renewable resources and practices like intensive farming have often resulted in pollution, leading to a weak ecosystem [38,39]. Further, developing countries like those in Africa often experience an "adverse economic geography" characterized by a scattered population and large geographical distance from markets, posing a barrier to innovative entrepreneurship [11]. Another significant study undertaken by Gallup et al. also found that the African region, particularly the SSA, owing to the peculiar geographic disadvantages contribute to persistent poverty [40]. The study outlined the key factors like high tropical concentration that affected health and agriculture, low coastal population density that adversely raised transport costs, and the distance from core markets also adversely affected trade opportunities and finally, the low overall population densities adversely hindered the infrastructure development in the region. Consequently, the SSA region has the lowest GDP per capita among the studied regions, linking poverty to geographic constraints.

Climate change as a systemic constraint

Climate change is increasingly acknowledged as a 'force multiplier' for agricultural hazards and socio-economic weaknesses [3]. Studies show that changing rainfall patterns and rising temperatures often lead to severe crop failures and an increased occurrence of extreme weather phenomena, like floods and droughts [41]. These climate changes more adversely affect the smallholder farmers, who generally have restricted adaptive capacity and lack the required resources to effectively deal with environmental disturbances [42]. Further, farming practices are progressively limited by escalating water shortages and the silting of essential water sources, which diminishes the dependability of surface water for extraction [43].

The cumulative impact of these stressors is especially noticeable in areas like SSA, where it is estimated that staple crop yields may fall by 10% to 20% by 2050 [44]. Although increased carbon dioxide concentrations can initially enhance plant growth, these benefits are frequently offset by higher temperatures that boost crop respiration and evapotranspiration rates [45]. The susceptibility of these systems is exacerbated by local environmental decline, including significant deforestation of key water sources, which lowers groundwater replenishment and decreases yearly water output [43]. As a result, the lack of climate-resilient practices and improved institutional backing will persist in jeopardizing food security due to the interaction between worldwide climate changes and local land-use modifications [42,44].

Doing Agriculture 4.0: Technological vis-à-vis Gender Issues

We have already argued that in today's changing technological environment, Agriculture 4.0 represents a new phase of technological transformation in farming, driven by digitalization, automation, and the growing need for sustainability. It combines advanced technologies such as precision farming, drones, robotics, artificial intelligence, big data analytics, and IoT-enabled sensors to improve resource efficiency, increase productivity, and minimise environmental damage. Other key components include smart irrigation systems , satellite mapping,

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and blockchain-based supply chain management, which enhance transparency and efficiency throughout the agricultural process, from production to market distribution.

However, as we have already indicated, despite its potential to improve efficiency and strengthen resilience, Agriculture 4.0 is not gender-neutral. As already argued, limited access to land ownership, institutional credit, and digital literacy often constrains their ability to adopt modern technologies. Further, the high cost of drones, sensors, and AI-based tools also leads to excluding the small and marginal farmers, among whom women are disproportionately represented. In addition, prevailing cultural norms and gender biases frequently prevent women from participating in training programmes and decision-making platforms where these technologies are introduced and promoted.

Thus, the digitalization of agriculture presents a paradox: while ICTs can enhance resilience, they risk widening inequality. Women often face restricted access to digital tools due to patriarchal norms and time burdens from household responsibilities. Without access to smartphones or training, women risk exclusion from Agriculture 4.0 innovations [14]. Innovative models such as shared leasing of equipment and mobile-based advisory services in local dialects can help bridge this divide.

However, in spite of such limitations, in certain cases, technological advancements are helping people in moving towards resilience in agriculture in a way to look beyond the traditional “weather-blind” practices. For example, WFBAS have proven effective in Bangladesh, where rice farmers using these services achieved higher net profits and reduced chemical use [24]. Moreover, digital technologies have also been shown to have the potential to enable smallholders to integrate into value chains, thus opening up opportunities for generating additional income streams [46].

Significantly, the success of such interventions depends on bridging scientific knowledge between the Global North and South to ensure locally tailored adaptation strategies. Nevertheless, the issue of the "digital divide" is also an important one. While tech-savvy youth in emerging economies are beginning to capitalise on these technologies, the lack of technical training, high operational costs and also the associated gender discrimination have also been shown to limit the uptake of these technologies at the wider level [38,47].

Issues relating to Financing of Sustainable Agriculture

Financing for sustainable agriculture has to be such that there is technological innovation and climate resilience, while at the same time, gender equity is also a part of this financing mechanism. Investing in climate-resilient practices such as precision farming, renewable energy use, and water-efficient irrigation can help improve agricultural productivity and protect farmers from climate shocks. However, if gender equity is not a part of this financing mechanism, then women farmers, who are a large part of the agricultural workforce and do not own agricultural land, do not have access to credit and do not receive proper training, might be left behind in terms of technological innovation and climate adaptation. Thus, when gender equity is made a part of sustainable agriculture financing, then sustainable agriculture does not just solve environmental problems , but also helps in empowering women farmers , who regard, a few issues need to be discussed, like the economic cost, recent technologies that need to be considered, what financing options for climate resilience we have and what public support measures are needed. Finally, we should also examine the role of the various kinds of institutions in this context.

The economic landscape of agricultural transformation

The transition to sustainable agriculture in developing countries is a capital-intensive process that requires a fundamental transformation of rural financial systems. Achieving the Sustainable Development Goals set out in the 2030 Agenda will require significant investment in both physical and human capital to transition beyond traditional low-yielding production systems [38]. Nevertheless, the agricultural sector in emerging economies, including the BRICS nations and SSA, is currently facing a "financing gap" due to the high initial investment costs of green technologies, which are currently beyond the reach of smallholder farmers [9]. Empirical studies have shown that while income growth in the sector does have the potential to result in a positive correlation with productivity due to the ability to ration more resources into equipment and other inputs, the lack of accessible credit is also an important systemic issue. Moreover, the "adverse economic geography" of rural areas, characterized by distance and dispersion, also acts to disincentivise private financial institutions to provide credit to green agricultural SMEs [11].

Financing agriculture 4.0: Drones, robotics, and smart systems

In the current scenario, use of Agriculture 4.0 technologies is also important for improving the utilization rate and reducing the carbon footprint of the agricultural sector [38]. The application of these "smart" technologies, however, is often contingent on the availability of public support through public financing and tax incentives. The literature indicates that agricultural organizations are more likely to apply eco-innovations if there is a supportive legal environment that cushions the risks associated with technology application.

The application of digital technologies is also important for improving the bankability of smallholder farmers. The application of mobile applications and ICT technologies is important for integrating the farmers into the markets and providing the required information for improving the risks associated with lending [47]. The tech-savvy youth are also seen as drivers of digitalization in emerging economies, although the high cost of technology, such as modern farming equipment, is a major challenge that requires innovative financing approaches such as leasing and sharing [9,38].

Financing climate resilience and risk mitigation

Climate change is a force multiplier for financial volatility and instability, especially in the agricultural sector. Changes in weather and the prevalence of extreme weather conditions such as drought and floods increase the risks of crop failure, and this, in turn, increases the cost of credit or limits the availability of credit for poor farmers [41]. To mitigate this, the use of WFBAS has been found to be a cost-effective and climate-resilient approach. For example, rice farmers in Bangladesh have been able to improve their crop yields, while at the same time, also reducing costs through the application of fertilisers and pesticides only when the weather is conducive [7].

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The economic viability of these climate-resilient agricultural practices is evident, as partial budgetary analyses have shown that replacing traditional "weather-blind" agricultural practices with WFBAS could generate significant net profit gains, thereby contributing to an increased national agricultural return while minimising environmental pollution through the judicious use of chemicals. Nevertheless, the expansion of these services depends on continued public investment in meteorological infrastructure and digitalization in the rural areas [7]. Scientific partnerships between "North" and "South" institutions are also important in the bid to promote the two-way transfer of technology and expertise, thereby ensuring that new technologies developed for climate adaptation are appropriate for the ecological conditions in the "South" [48].

Public support, subsidies, and the role of institutions

Institutional support and the role of the government are significant factors that influence the growth and sustenance of modern agricultural enterprises [9]. The implementation of Agricultural Sustainable Development Plans (ASDP) in China, for example, has been instrumental in the promotion of agricultural carbon neutrality through the development of more efficient operational methods. The provision of subsidies and grants by the government could be the "lifeline" in the promotion and development of eco-innovations in the form of organic farming and integrated pest management [10]. However, the efficacy of these subsidies remains debatable, and some literature indicates that unless they specifically target issues of eco-efficiency, they may even encourage unsustainable high-intensity farming practices [49]. It is, therefore, imperative that policy guidelines address issues of gender-responsive finance, keeping in view the credit constraints faced by women farmers, who often lack collateral for accessing finance through traditional lending channels [9,13].

Towards Framing an Integrated Policy Framework for Sustainable and Gender- Just Agriculture

In order to meet the 2030 Agenda for Sustainable Development, the policy environment would need to transcend "tech-fixes" and integrate inclusive finance with technology and gender equity. An integrated approach would ensure that inclusive finance and technology are mutually supportive dimensions for sustainable development [9,13]. The following policy measures can play a pivotal role:

Reform of credit systems and financial inclusion

The conventional approach to agricultural finance, based on a collateral-based system, is inherently biased against women farmers, who often lack formal land ownership [9,13]. To bridge the "financing gap," governments would need to promote green agricultural financing through public-private partnerships, providing low-interest loans for high-cost technologies such as precision irrigation and renewable energy [9]. The success story of ASDP, such as those implemented in China, highlights the potential for an effective policy environment to promote agricultural development while ensuring carbon neutrality. The crucial element is to ensure that these financial instruments take into consideration the "double burden" faced by women, who often have to balance domestic and agricultural responsibilities , restricting time for vocational training [49]. Technology-specific loans would ensure that the reform of the credit system directly supports sustainable agricultural productivity.

Inclusive digital transformation and extension services

Scaling climate-smart technologies (CST) requires the "leapfrogging" concept, wherein tech-savvy youth and women are provided with the requisite technological and vocational skills [9,47]. The priority is the integration of WFBAS into the country's extension system. The empirical evidence suggests that WFBAS helps farmers make highly informed decisions regarding the use of water and other input resources, thereby reducing the risk associated with extreme weather conditions and maximizing profitability [7]. The reengineering of the extension system is essential to ensure the reach and accessibility of CST to women, wherein the extension workforce is augmented with more women extension workers trained in local dialects to overcome the social-cultural barriers and male domination in the access to technical knowledge [13,47]. The mobile-based platforms are helpful in the empowerment of women as the information is sent to them, bridging the gender gap in the digital divide [13].

Realigning incentives, subsidies, and partnerships

The subsidy policies are often biased towards unsustainable high-input farming, as the over-subsidization of nitrogen-based fertilizers led to soil degradation without an increase in crop yield. The shift to the "balanced fertilization policy" using the 4:2:1 ratio of NPK, along with soil testing, can be achieved in a "win-win" scenario for productivity and the environment [39]. The private sector must adopt "Gender-Just" Corporate Social Responsibility (CSR) policies. The policies must ensure the investment of a significant percentage of the CSR budget in women's roles in food production, processing, and preservation to ensure equitable access to revenue and credit [50]. The local efforts must be supported by the North-South model of scientific cooperation based on the principles of trust and equity to ensure the transfer of technology according to the local ecological conditions [48].

Legal reform and structural empowerment

The issue of securing ALO for women stands out as the most crucial policy intervention for sustainability [51,52]. Legal reform is an imperative step in breaking away from patriarchal family laws, with the support of rural legal aid centers for women to claim their rights to inheritance. It has been observed at the grassroots level that "if women claim their right to land, there is an immediate improvement in income and an increased willingness to invest in sustainable practices" [52]. In addition to this, for sustainability, it is crucial for women to be part of social participation through women's professional associations and cooperatives for "learning by training" and social embeddedness. There is a statistical correlation between high levels of women's empowerment in farm management and social decision-making with high levels of eco-efficiency and maintaining soil biodiversity [49].

Based on the above discussion and also with a reference to Table 3, a summarized graphical presentation of the various impacts of agricultural policies often has on its productivity and sustainability has been shown in Figure 2.

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Table 3. Impacts of agricultural policies on productivity and sustainability.

PSE* Category	Policy Type	Impact on Technical Efficiency	Impact on Total Factor Productivity	Environmental Indicators Affected	Direction of Environmental Impact	Summary of Theoretical Findings
Category A	Market Price Support (MPS) and Output Payments	Significantly negative (48% of findings for physical unit payments)	Significantly negative (83% of findings)	Water quality, greenhouse gas emissions, biodiversity, nutrient loadings	Generally negative due to intensification and land clearing; reduction may lead to negative impacts through land abandonment	These policies provide incentives for output expansion and input-use intensification by proportionally increasing the final revenue received by producers.
Category B1	Payments based on variable input use (water, fertilizer, pesticide, fuel)	Significantly negative (100% of findings)	Significantly negative (100% for insurance-based input support)	Greenhouse gas emissions, nitrogen runoff, phosphorus balance, biodiversity	Generally negative if subsidizing chemicals/water; positive if subsidizing environmentally-friendly inputs/practices	These policies provide incentives for output expansion and input-use intensification by proportionally increasing the final revenue received by producers.
Category B2	Payments based on fixed capital formation (Investment support)	Mixed: 56% significantly positive; 33% neutral; 11% negative	Significantly negative (80% of findings)	Greenhouse gas emissions, water take, soil and water management	Mixed; depends on the type of capital; positive for adaptive/environmental capital, but can lead to increased intensity	Investment support can adopt productivity-enhancing improvements but may lead to negative environmental impacts if farmers increase production.
Category C	Coupled payments (based on current area, animal numbers, receipts or income)	Significantly negative (48% negative; 31% neutral; 21% positive for physical unit payments)	Significantly negative (83% of findings)	Water quality, greenhouse gas emissions, biodiversity, fertilizer/chemical use	Generally negative due to incentives for intensification and maintaining production on sensitive land	Farmers are likely to maintain or increase cropped area or herd size to qualify for entitlements, increasing environmental pressures.
Category C	Subsidized crop insurance	Not in source	Significantly negative (100% of findings)	Climate change adaptation, soil degradation, fertilizer/chemical use, wetland drainage	Generally negative; induces risk-taking behavior and maladaptation, and encourages production on marginal land	Insurance reduces the probability of loss, creating incentives to plant on arable land not otherwise considered and potentially increasing input use.
Category E	Decoupled payments (Fixed rate)	Mixed: 40% neutral; 32% positive; 28% negative	Mixed/Positive (50% positive; 36% negative; 14% neutral)	Biodiversity, landscape mosaic, water quality (via cross-compliance)	Mixed; neutral impacts on production but can lead to landscape homogenization and biodiversity decline	Not linked to current production; theorized to minimize distortions but can slow structural change through capitalization into land values.
Category C or F2	Agri-environmental payments	Mixed: 46% significantly negative; 32% significantly positive; 21% neutral	Neutral/Insignificant (67% of findings)	Fertilizer/chemical use, GHG emissions, nutrient loadings, biodiversity	Generally positive or neutral; effectiveness depends on additionality and scheme design	Usually, voluntary payments for abiding by environmental constraints; success depends on threshold effects and spatial targeting.

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Category F1	Long-term resource retirement (e.g., US CRP, afforestation)	Not in source	Can be positive if retiring marginally productive land	Soil erosion, water quality, wildlife habitat, carbon sequestration	Significantly positive; decreases soil erosion and improves ecosystem services	Involves multi-year agreements to remove land from production for conservation; productivity may rise due to the exit of poor land.

Author's presentation based on DeBoe G and others [36].

*PSE= Producer Support Estimate.

Figure 2 indicates that various support mechanisms significantly influence farm productivity and natural resource management. It categorises agricultural policies into high-distortion and strategic targeted ones, with 83 percent of studies indicating negative productivity impacts associated with production volume-linked support. High-distortion policies, such as market price supports and input subsidies, contribute to environmental degradation through intensive monocultures and chemical overuse, resulting in heightened greenhouse gas emissions and water pollution. Conversely, decoupled payments can enhance economic performance while minimizing nutrient imbalances, although their success relies on "cross-compliance," linking environmental benefits with mandatory conservation practices. Thus, Figure 2 highlights potential land abandonment risks if support is removed without targeted policies to preserve biodiversity. Farm-level technical efficiency data aligns with these findings, revealing that 90% of observations indicate negative impacts due to high support dependency, while decoupled payments show a more balanced effect.

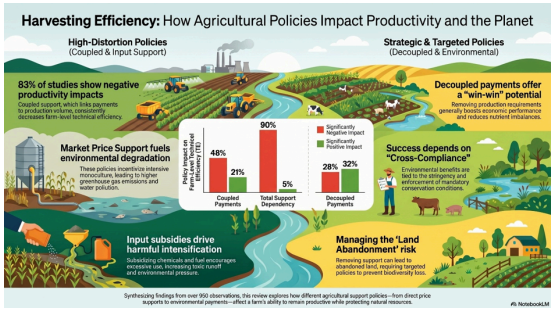

Figure 2. Impacts of agricultural policies on productivity and sustainability.

Source: Author's presentation. Generated using AI (NotebookLM).

Notes: Coupled support pertains to agricultural payments linked directly to existing production rates, including particular outputs, inputs, crop acreage, or livestock quantities. On the other hand, decoupled support pertains to agricultural payments linked to past entitlements that do not necessitate current production, enabling farmers to react more directly to market signals.

Major Discussions and Policy Relevance

This discussion presents a comprehensive framework for addressing critical agricultural challenges in developing nations. The major arguments and policy relevance of this study include: first, a major focus is on promoting WFBAS to combat "weather-blind" production, which leads to crop failures and financial instability for smallholders. By using empirical data from rice farming in Bangladesh , it suggests WFBAS enhances farmers' decision-making regarding fertilizers and pesticides, optimizing their use according to weather conditions. This reduces input costs and environmental harm, while increasing profits and agricultural yields [7].

Second, to tackle the financing gap hindering Agriculture 4.0 adoption, the study recommends a shift from traditional collateral-based lending, which often sidelines those lacking formal land titles [9,13]. Evidence shows green SMEs face credit exclusion due to rigid policies. The proposed integrated policy response includes technology-specific loans and green agricultural financing via public-private partnerships, facilitating innovations like precision irrigation and robotics, thus aiding rural populations in transitioning to the digital era [11,47].

Third, highlighting eco-inefficiency, empirical evidences cited in this paper demonstrates a correlation between women's empowerment and improved environmental performance on farms [49]. As women attain higher empowerment levels, sustainable practices increase, such as plant cover diversity and reduced pesticide use. This suggests the need for reengineering extension services to incorporate more female workers trained in local dialects, ultimately bridging the gendered digital [13,47].

Finally, the paper addresses ecological damage from distorted subsidy regimes by advocating for balanced fertilization policies linked to soil testing, securing soil biodiversity while ensuring food security [12,39]. Additionally, it suggests legal frameworks for women's ALO could enhance household income and investment in sustainable technologies [51,52]. Overall, this multi-faceted approach aims to create a resilient agricultural future aligned with the 2030 Agenda for Sustainable Development [1]. The roadmap towards feminization of sustainability in the technology-driven era of Agriculture 4.0 has been graphically shown in Figure 3.

Figure 3. Feminization of sustainability: an integrated path to agriculture 4.0.

Source: Author. Generated using AI (Notebook LM).

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Figure 3 illustrates the intersection of gender equality, technology, and financing in shaping sustainable agriculture, highlighting systemic barriers women face regarding access to resources. The paper stresses that empowering women through land ownership, technology access, and finance not only fulfills social equity but is crucial for ecological efficiency and food security. An integrated approach is essential for advancing sustainability in these agricultural environments, ultimately contributing to a better future.

Conclusion

This paper argues that sustainable agriculture in developing countries requires more than just technological advancements; it demands a unified approach that includes financing, digitalization, and gender equality. It emphasizes the feminization of sustainability, asserting that empowering women is vital for achieving ecological effectiveness. Evidence from Asia and SSA indicates that secure land tenure, gender-sensitive financing, and accessible digital infrastructure are crucial for transforming agrifood systems. Notable examples such as Bangladesh's weather advisory services, Ethiopia's women-led dairy cooperatives, and Ghana's gender-sensitive cocoa certification demonstrate that integrating supportive legal frameworks with gender-focused initiatives fosters eco-innovative solutions and enhances sustainability.

However, the research acknowledges limitations, primarily relying on secondary sources that lack empirical generalizability. Future studies should incorporate field surveys, econometric analysis, and longitudinal research for a more robust understanding of gender-responsive initiatives. Policymakers in developing nations are advised to implement public support measures and gender-specific targeting to ensure women farmers are included in technological transitions.

Disclosure Statement

No potential conflict of interest was reported by the author.

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