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Review

A REVIEW OF AGRICULTURAL EXTENSION INNOVATIONS ACROSS THE WORLD - A CRITICAL ANALYSIS

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Abstract

Agricultural extension has undergone substantial innovation across countries and regions as governments and development agencies have sought more effective ways to transfer agricultural knowledge and technologies to farmers. This review examines major extension innovations from Africa, Asia, Europe, Australia and North America, including participatory extension systems, farmer field schools, pluralistic and private extension models, public–private partnerships, farmer organizations, digital advisory services, call centres, expert systems and technology centres. Across these cases, the literature shows that effective extension is not limited to information delivery; it also depends on farmer participation, institutional coordination, access to resources and responsiveness to local social and economic conditions. Many of the innovations reviewed move extension away from a top-down model toward more demand-driven, collaborative and context-specific approaches. The review suggests that no single extension model is universally appropriate. Instead, agricultural extension systems are most effective when they combine technical advice, institutional support and mechanisms that strengthen farmer learning, inclusion and adoption of innovations.

Keywords: Agricultural extension; extension innovations; farmer field schools; pluralistic extension; public–private partnerships; farmer participation; global review

Introduction

Agricultural extension innovations have played a central role in transferring technologies from research systems to farmers. Across countries, extension approaches have varied according to local priorities, institutional arrangements, cultural conditions and resource availability. As a result, extension has evolved from a predominantly top-down technology transfer function into a more diverse set of participatory, pluralistic and technology-enabled systems. These innovations have improved the delivery of agricultural knowledge, strengthened farmer engagement and supported more efficient adoption of improved practices. This paper reviews major agricultural extension innovations from different regions of the world and critically examines their contributions, strengths and limitations.

Agricultural Extension innovations in African countries

Participatory Demonstration and Training Extension System (PADETES), Ethiopia

Ethiopia has historically adopted technologies through extension services (Jordan & Guerzoni, 2020). It is important to develop efficient, comprehensive, need-based and participatory agricultural extension services for raising rural household income

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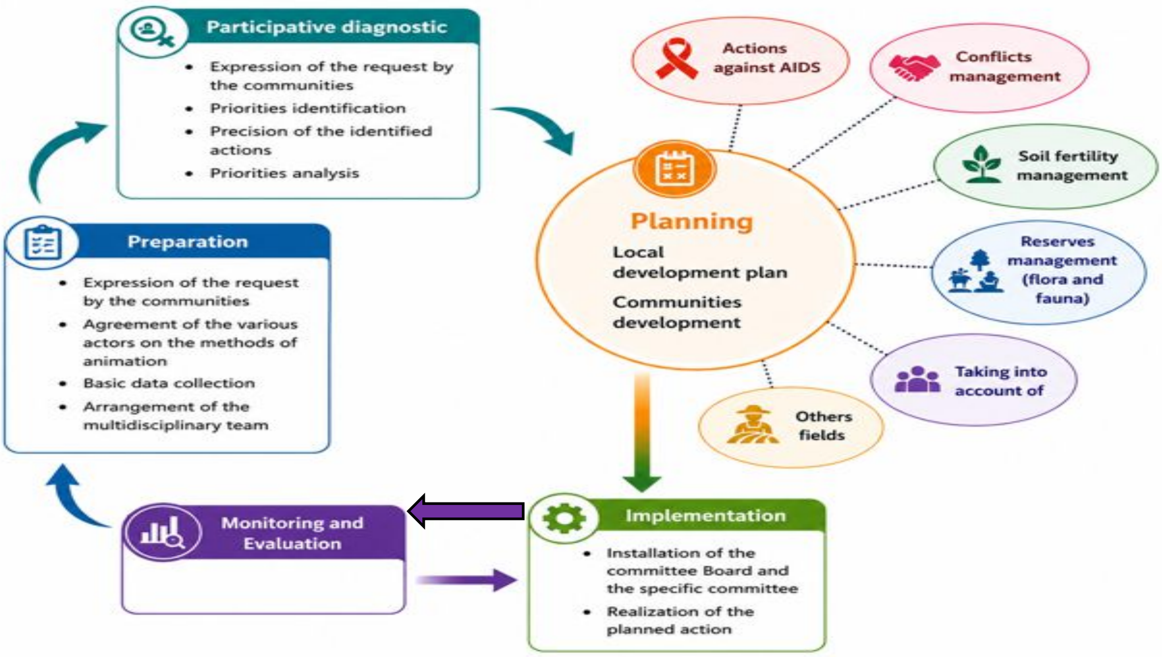
and welfare (Ambaye et al., 2021). In PADETES, smallholder farmers' productivity is increased; incomes are improved through enhancing productivity; farmers are empowered to participate actively in the development process; food production is self-sufficient; farmer organizations are established; export crops are increased; natural resources are conserved; and farmers' organizations are encouraged (Davis, 2008). The Extension Management and Training Plot (EMTP), typically a half-hectare on-farm demonstration plot run by farmers and used to instruct other farmers and extension workers on good agronomic and farm management practices, served as a vehicle for the model's promotion of the production of cereals (Egziabher *et al.,* 2011). This programme provided smallholders with improved seeds, fertilizer, pesticides, and other improved production practices to increase their productivity (Wubneh, 2007). A typical extension distributing fertilizers, not providing to provide technical advice (Davis, 2008). In contrast, other studies have found that extension workers and rural services significantly contributed to the massive increase in agricultural production (Ayele et al., 2005). Fewer women farmers are participating in PADETES (Lucky & Achebe, 2013).

National Agricultural Advisory Services (NAADS), Uganda

The NAADS extension service was established by the government of Uganda in 2001 as an innovative farmer-driven extension service aiming to improve farmers' productivity and livelihoods by introducing profitable agricultural enterprises and improved technologies (Benin *et al.,* 2011; Swanson & Rajalahti, 2010) The PMA's Plan for Modernizing Agriculture priorities included promoting agricultural research and technology; improving agricultural advisory services; improving agriculture skills and knowledge; improving rural finance access; promoting agro-processing and access to markets; and promoting sustainable natural resource management (Kasirye, 2013; Larsen *et al.,* 2009) . A key success element of NAAD was technology development, where revolving credit was provided to farmers to learn new skills and adopt new technologies and increase productivity and per capita income (Olayemi *et al.,* 2021). (Birner & Anderson, 2007) enumerated some of the features of NAADS, including decentralization, outsourcing, subcontracting, farmer empowerment, market orientation and cost recovery. In addition to providing farmers with current information, the programme increases farmer productivity via technologies and equips farmers with skills and knowledge so they can move from subsistence to commercial farming (Kasirye, 2013).

Participatory Approaches in Benin

A participatory approach is most often used in rural areas for diagnosing problems. As part of this diagnostic process, village communities identify and analyse their local assets and constraints, and develop strategies to exploit those assets and eliminate constraints (Philibert, 2008).



Source: (Philibert, 2008)

Farmer to Framer Extension in Ghana

Farmer field schools (FFS) were introduced into sub-Saharan Africa in the mid-1990s as a participatory method for learning, technology development, and dissemination, based on adult-learning principles. They are currently used in 27 SSA countries (Braun et al., 2006). FFS relies heavily on farmer-to-farmer information exchange to spread new ideas. Evaluation of the FFS' impact in Ghana indicates a high level of communication between farmers using techniques learned through the FFS farmers. FFS graduates organized small group meetings on their own. Several participants mentioned giving unsolicited advice to neighbours, although this was less common the majority of exchanges focused on specific technologies or management practices. Communications among FFS participants, however, tended to focus on emerging problems and technology spread (Ackah-Nyamike Jnr, 2008)

Pluralistic Extension in Mozambique

Mozambique has had a pluralistic extension system since the early 1990s (Gemo *et al.*, 2013). NGOs and private commodities extension organizations, in addition to the public extension system (MOA), play a significant part in Mozambique's pluralistic extension system.

Extension service	Public Extension System	Private extension organization	NGO
Focus on	The unified extension (crops, livestock, natural resource management, farmers' organizations, and market development support)	Commodity-oriented extension mainly for cotton and tobacco, and emerging out-grower farming for sesame	From often narrow-focused (for example only market development support)
How	providing free services through extension networks based at villages/ community/ district levels throughout the country	Offering sub-contracts (input and services credit) for smallholder farmers to grow and sell the harvest to the contractors, in agro-ecologically suitable regions	Offering free services through local extension agents at villages/ communities and district levels throughout the country

SOURCE: (Gemo et al., 2013)

Paid Private Extension System in Uganda

A system of paid private extensions has been implemented in Uganda This extension approach encourages farmers to pay certain costs related to knowledge and technology extension and to reduce public expenditures on extension (J. Anderson & Van Crowder, 2000; Babu *et al.*, 2015). In some nations, like Uganda, where a private extension has been adopted, (J. R. Anderson *et al.*, 2007; Babu *et al.*, 2015) observed that the privatization of agricultural extension services is reliant on the financial viability of the specific service. Farmers must have discretionary income to be "paid for," suggesting that this approach is best suited for commercially based farmers that operate as market rivals and have exportable crops This shows that its goal is to support industrial agriculture Systems of paid private extension enable farmers to identify their issues and look for a suitable solution from service providers (Lindner, 1993)

Commodity Extension system in Mali and Zimbabwe

A commodity-based extension system combines a variety of activities for promoting production, including technology extension, research, input, producing marketing and pricing, under one administration or organisation structure (Kidane & Worth, 2016). Extension delivery is typically efficient, focuses on just one product, and the organisation is typically small and mostly focused on inputs (Kenmore, 2002). According to (Anandajayasekeram, 2008; Eicher, 2007), the colonial forces introduced this paradigm to smallholder cotton farmers in Mali, Malaysia, and other francophone nations. As part of the commodity system, research and extension are self-funded through coordination with public extension systems. In addition, the system has been primarily organized by private firms that produce and market very important industrial cash crops (Kidane & Worth, 2016). A number of successful produce grower schemes have been established in some countries in Africa, including Zimbabwe (FAO 2016) due to strong support from private firms.

National Agriculture and Livestock Extension Programme (NALEP) in Kenya

The National Agricultural and Livestock Extension Programme in Kenya, which promotes common interest groups (CIGs) among farmers, was created in the year 2000. The widespread consensus is that groups advance technologies more quickly than individual farmers (Anandajayasekeram, 2008). The NALEP aim was to turn agriculture and livestock into a sustainable system to achieve food security, wealth creation, and national economic growth through science-based, market-oriented, competitive, and lucrative agricultural systems (Chhettri, 2011). A problem to be addressed is the training and retraining of the extension staff on matters of marketing, packaging, and developing crops and animals to ensure they fulfil the expectations of farmers (Ngugi *et al.,* 2014)

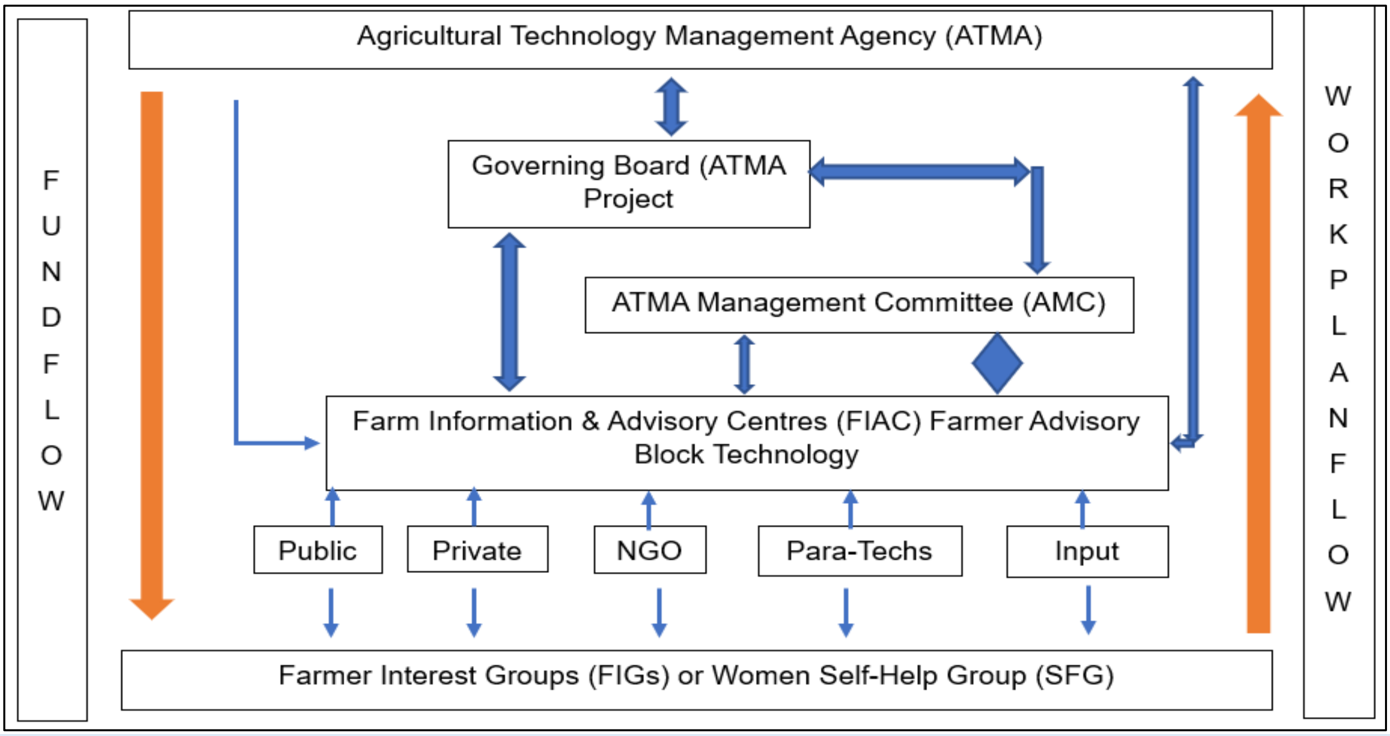
Public Private Partnership in Morocco

A case study from Morocco offers an intriguing example of institutional innovation and collaboration; the Moroccan tomato value chains show the usefulness of collaboration, interaction, and knowledge exchange in enhancing the effectiveness of the value creation process. The situation highlights how collaboration between farmer's organizations, the private sector, higher education institutions, and government agencies led to increased yields and quality (Mondal, 2013)

Agricultural Extension Innovations in Asia

The Agricultural Technology Management Agency (ATMA), India

Agricultural Technology Management Agency (ATMA) is a self-governing and market-driven Indian extension agency that represents a shift from technology transfer to better coordination (Singh *et al.,* 2006). Farm income and rural development are the primary objectives; extension services should be integrated across departments; and farmer organizations should be involved to increase productivity (Birner *et al.*, 2009; Swanson & Rajalahti, 2010) ATMA is a government extension initiative that aims to support state extension reform aimed at revitalizing state extension systems (H. Gupta & Shinde, 2013) . In India, the ATMA approach has been regarded as the most successful agricultural extension reform because it has been adopted in all 600 districts within five years (J. R. Anderson et al., 2007; Davis, 2008). A cross-section of stakeholders makes decisions on ATMA Governing Board priorities and extension activities (Ferroni & Zhou, 2012; Singh et al., 2006). According to (Ferroni & Zhou, 2012) some of the constraints of ATMA are the lack of qualified local manpower; delivery mechanism issues; technical and financial support and a clear framework for partnerships.



Source: (Singh *et al.,* 2006)

Krishi Vigyan Kendra (Farm science centre), India

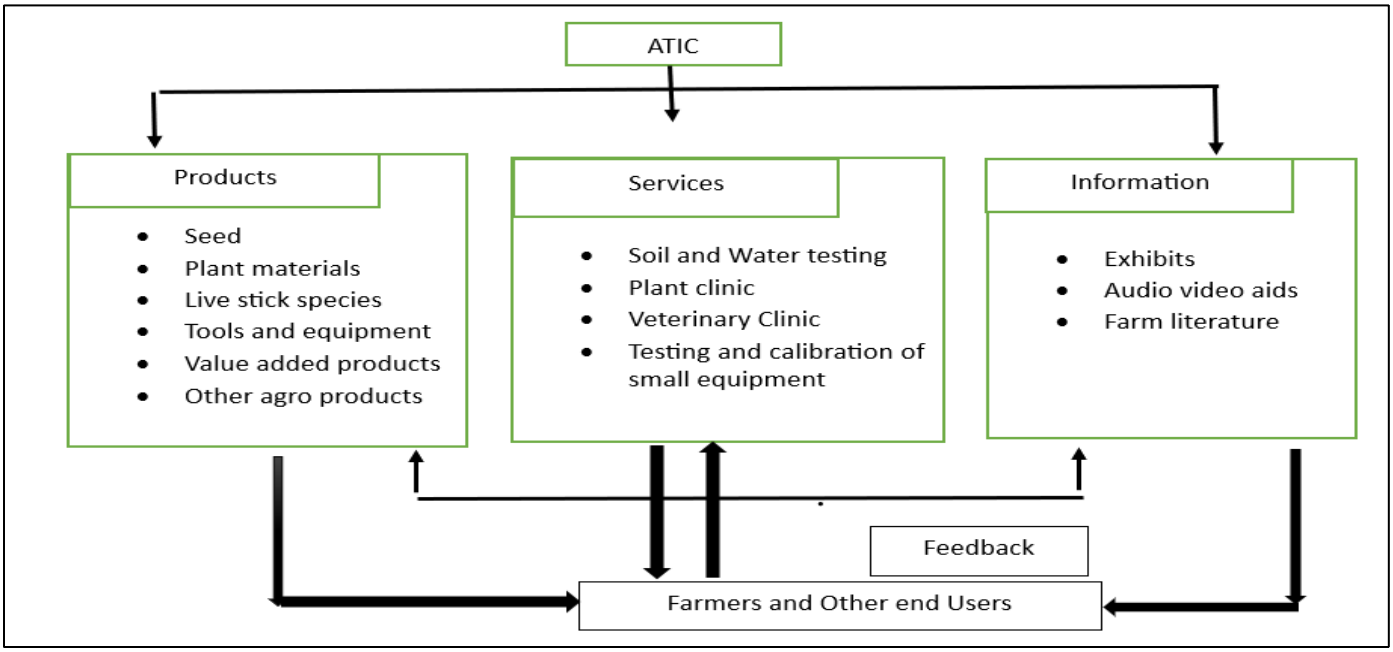
Krishi Vigyan Kendra was introduced by the ICAR (Dubey *et al.,* 2008) Krishi Vigyan Kendra (KVK) is an innovative science-based institution whose participants include scientists, subject matter experts, extension functionaries, and farmers. The main objective of Krishi Vigyan Kendra is to improve the knowledge of the trainees about improved farm technologies, as knowledge is a cognitive component of an individual's mind and plays a crucial role in both covert and overt behaviour (S. Gupta & Verma, 2013). KVKs are grassroots organizations that assess, refine, and demonstrate proven technologies in different micro-farming situations (Das, 2007). Following (Kokate *et al.,* 2011), the KVK's mandates have changed with time as they gained strength and spread. The KVK began in 1974 with the mission to impart vocational training. On-farm testing and demonstration of technologies became the focus of the 1990s. During the Tenth Plan (2002-2007) technology assessment and refinement focused, and During the Eleventh Plan, KVKS acted as a knowledge and resource centre of agricultural technology. KVK can significantly improve socioeconomic status as well as training levels among different classes of trainees, according to (Ajrawat & Kumar, 2012).

Flag method of Extension, Agricultural University Innovation, India

Flag method extension is a simple innovative effective transfer of technology tools developed by ANGRAU University where Extension persons use yellow, pink, and white colour flags to provide information about problems of crops and remedial measures in the field without a farmer present and general information on the backside of the flag (Mondal, 2013). The Flag method solves the problem immediately and builds rapport with extension scientists and strengthens the scientist-farmer linkage (Mondal, 2013).

Agricultural Technology Information Centre (ATIC), India

ATIC was established in 1999 by Punjab Agricultural University (PAU). An Agricultural Technology Information Centre (ATIC) connects the various units of a research institution with end users (farmers) and intermediary users to support decision-making and problem-solving exercises (D. Singh & Kalra, 2019a) . An expert in the fields of entomology, plant pathology, soil science and agronomy provide advice to farmers regarding their field problems. Agricultural advisory services are an integral part of the array of market and non-market entities and agents that provide critical information that can improve the welfare of farmers and rural people (J. R. Anderson, 2008) . In addition to advisory services, ATIC sells technological products, farm literature, and plant clinic services, and offers a helpline (D. Singh & Kalra, 2019b).



Source: (Mondal, 2013)

Kisan Call Centre (KCC), India

On January 21, 2004, the Department of Agriculture & Cooperation (DAC), Ministry of Agriculture & Farmers Welfare, Government of India launched Kisan Call Centre (KCC) to offer free tele agricultural advisory services to farmers. By calling 1800-180-1551, the farming community can receive services from 6 a.m. to 10 p.m. every day in their local language (Koshy & Kumar, 2016)

The operation mechanism of KCC is presented following (Chole *et al.,* 2010)

Level :1 Answering the farmer's query immediately handled by Agri graduates

Level: 2Transferring the unanswered question to an agricultural university or other technical institutes for an immediate response (SMS)

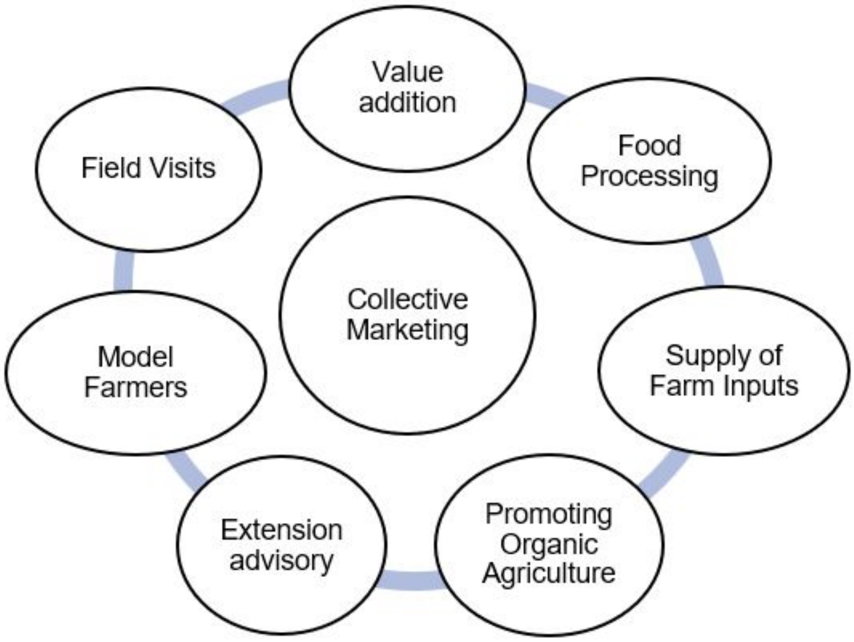
Level :3 Experts will examine and provide the farmer with a detailed answer by mail, telephone or visit (SMS) at the nodal office

Group Approach in India

The transition of the public, private, and NGO expansion from individual to collective approaches helps extension planning and execution. It increases farmer accountability and promotes sustainability by allowing for group participation in decision-making, access to credit, value addition, and marketing (Rasheed Sulaiman, 2003)

Farmers producers' organisations (FPO) in India

FPOs aren't new to India. The cooperative movement started in India in the 1930s. Currently, several cooperatives represent about 70% of the agricultural producers in the country (Ministry of Agriculture, Govt. of India 2015). Most Indian farmers own less than five hectares of land, so they form farmer-producer organizations to overcome the challenges (Derle & Hasan, 2022). Farmers 'producers organisations like the Velliangiri Farmer Producer Company Ltd (VFPCL) in Coimbatore are essential in enhancing farmers' knowledge and abilities through information sharing (Abraham & Raj, 2022).



Source: (Abraham & Raj, 2022)

The Farmer Field School Model in Philippines and Indonesia

The Farmer Field School (FSS) extension concept was developed in the Philippines and Indonesia in 1989. The FFS extension approach is a participative technology development and distribution strategy that offers farmers the chance to learn useful fieldwork skills (Olayemi *et al.*, 2021). FFS proved highly effective in lowering the usage of insecticides in the Philippines and Indonesia. The FFS model includes intensive training exercises that employ participatory methods to help farmers develop their analytical knowledge and skills, critical thinking, and creativity. As a result, they are able to learn how to make better decisions not only in their farming operations but also in their daily activities , at least once a week on a member's farmland (Anandajayasekeram, 2008; Kenmore, 2002). (Anandajayasekeram, 2008) listed a few difficulties with implementing FFS in developing nations, such as inadequate exposure of research and extension staff to the concepts and practices of FFS, rivalry and conflicts of interest between various donor agencies, sharing of proceeds from the school approach, and lack of coordination of FFS activities.

Family Approach Extension in Bangladesh

The International Maize and Wheat Improvement Centre's (CIMMYT) research in Bangladesh revealed higher adoption rates of wheat technologies when all family members were trained together which gave rise to the idea to test the family approach in extension in Bangladesh (Meisner, 1998; Meisner *et al.,* 2003). The Department of Agricultural Extension (DAE) in Bangladesh conducted training a full family (both husband and wife with children) to half a family (husband and wife without children) and spouse alone through the Poverty Elimination through Rice Research Assistance Project (PETRA), which was supported by the Department of International Development (DFID) The training courses covered – rice cultivation, plant health management, the post-harvest operation, and modern rice seed production (Sagar, 2013). One and half years later, a two-week evaluation mission revealed that training the entire family or half a family (husband and wife without children) had more advantages than training either spouse alone, particularly in terms of gaining more knowledge, applying new technologies, increasing rice production, and influencing others in the community to adopt technologies

Drawbacks according to (Mondal, 2013)

- Young children can occasionally make training sessions distracting.
- In certain places, removing social and cultural barriers that prevent women from participating in training is still a problem.

Pocket Package Strategy (PPS)in Nepal

The first step in implementing PPS is selecting viable pocket locations for chosen crops or commodities. Considerations for selecting pocket areas include their geo-environmental suitability, natural resource endowment, and accessibility to physical infrastructure. All Agricultural Knowledge and Information System stakeholders, including input suppliers and dealers, are expected to collaborate in each pocket region to attain the shared objective of higher productivity. A review of the PPS's implementation by several independent organisations and the implementing agencies revealed that the PPS tended to direct public sector agricultural extension agencies' attention away from the poor and disadvantaged people who reside in marginal areas and towards resource-rich areas and resource-rich farmers (Ojha & Basnyat, 2008)

Agricultural technology parks in Sri Lanka

A quick information dissemination mechanism was recently introduced at this exhibit. Visitors will be able to see live demonstrations of some of the latest technical recommendations for food crops and self-explanatory digital posters. If visitors need further clarification, agricultural instructors are assigned to each section. Researchers assist with creating demonstrations and deciding on technical content. The Technology Park has become a popular agro-tourism site and serves as a "live agricultural university" for those interested. A park is also a place for students to discover learning (Hossain *et al.,* 2014)

Field Days in Sri Lanka

Even though field days are planned as a regular extension activity, researchers are occasionally invited when a notable field event takes place. They get a chance to talk to farmers, learn about various farming settings, and exchange experiences with farmers and extension specialists. In addition, field days are held by the Research Institute to demonstrate new technology. Researcher and extensionist communication can grow as a result of this (Hossain *et al.,* 2014)

Expert System, World Wide

According to (Prasad & Babu, 2008), an expert system is a technique for extracting knowledge-based information. It is a computer application created to encourage an expert in a certain field or profession to solve problems. Components Expert System presented following (Sriram & Philip, 2016)

1. ***The crop doctor:*** The crop doctor is the essential element of the expert system. With the aid of dot net and SQL server, it was created using a "if and then" rule-based software. The method only uses images to diagnose nematodes, illnesses, pests, and nutritional problems.

2. ***Decision Support System:*** Decision support systems help farmers make informed decisions about regular crop production procedures. It has been effectively designed and implemented to use DSS to provide information and recommendations on effective fertilizer usage, decreasing the use of herbicides, plant protection techniques, risk management for the environment, seasonal climate forecasting, land use planning, and other topics.

3. ***Information system:*** The information system is a web-based static and dynamic database that has been loaded with all the material and technologies relevant to the crops in question. This enables extension personnel and scientists to access up-to-the-minute data on the crop for their own use.

Comax: A cotton crop management expert system is called COMAX. The expert System is combined with the Gossym computer model, which promotes the growth of the cotton plant (Lemmon, 1986)

Cuptex: A cucumber production management expert system utilized by the Egyptian Ministry of Agriculture's agricultural extension department as well as the private sector. For fertigation plant care and disorder correction, CUPTEX consists of three expert systems (Rafea *et al.,* 1995)

Pomi: An expert system for integrated pest management of apple orchards was developed in Italy (Gerevini *et al.,* 1992).

Wheat Pakistani Expert System: (Khan *et al.,* 2008) created a web-based expert system for Pakistan's wheat crop.

Pluralistic Extension in Philippines

The Agriculture and Fisheries Modernization Act (AFMA) and the devolution of general agricultural extension in 1993 resulted in an implied pluralistic extension system in the Philippine agricultural extension system (Palis & Flor, 2008) . There are five key players in the nation, including

1. Local government units (LGUS) of the Department of Interior and Local Government
2. Bureaus and attached agencies of the Department of Agriculture including Agricultural Training Institutes (ATI)
3. State College and Universities (SCUs) of the Commission on Higher Education
4. Non-Governmental Organisations (NGOs), and
5. The Commercial private sector

Extension services for provinces, cities, and municipalities are no longer a primary responsibility and function of the Department of Agriculture (DOA)

Radio Programme, Nepal

Since its introduction in Nepal in 1951, radio has been the most successful medium for mass communication. In the nation, there are reportedly more than 3.0 million radios. Informing local farmers about agricultural commodity prices is a key function of FM stations. In addition to this, they are valuable resources for farmers to learn about agricultural practices directly from practitioners and to stay informed of significant agricultural events (Hossain *et al.,* 2014).

Agricultural Extension Innovation in Australia

Pluralistic extension services in Australia

According to (Klerkx & Nettle, 2013), the Australian agricultural research development and extension system (RD&E) is pluralistic and exhibits many characteristics of other countries' privatised extension systems. However, the Australian RD&E system is acknowledged as being extremely complicated (Hunt *et al.*, 2012, 2014), being mostly driven by industry and driven by a number of public, private, and industry-good initiatives. (Shared Government-Farmer Levy-Arrangements by Agricultural Commodity) and farmer-owned R&D organisations, as well as Vocational training organisations engaged in agricultural extension. According to (Prager *et. al.,* 2016), we define a typology of advising and extension actors to distinguish between public actors (government), private players (commercial and independent fee-for-service advice), farmer-owned organisations, and third-sector actors (NGOs)

Agricultural Extension Innovation in European Countries

Cost Recovery Approach in Britain

The Agricultural Development and Advisory Services (ADAS) in England and Wales, are notionally "commercialized" and operate on a partial cost-recovery basis. Clients of ADAS pay a fee for advice which formerly was free of charge. This process of cost recovery introduced in 1987, was directed toward the agency receiving 50 percent of its income from commercial fees by 1993-94 (Bunney & Bawcutt, 1991)

Privatization in Netherlands

By shifting field extension staff to farmers groups with initial financial backing from the government, The Netherlands privatized around half of its public extension service in 1990. According to (Proost & Röling, 1992), the board that oversees the privatized extension service is equally composed of representatives from the government and farmers' organizations.

Farmer Association in Germany

Farmers' unions, marketing cooperatives (typically on commodity quality and pricing issues), and other organizations that specialize in providing information and assistance to farmers concerns) and farmer associations (via, for example, advising and controlling actions). These extension services are often supported by a combination of membership fees and state subsidies, however, their funding model is highly diverse (Hoffmann *et al.*, 2000)

Semi-Privatized Extension in Germany

While private agricultural extension specialists can provide their services either as an individual, in a partnership with other advisers, or as a corporation each extension agent and a firm must formally register with the state. Each state has now experienced the emergence of a regulated market for extension provision. Even when the private sector provides extensions, the state continues to play a role in covering the costs in each case (Hoffmann *et al.,* 2000)

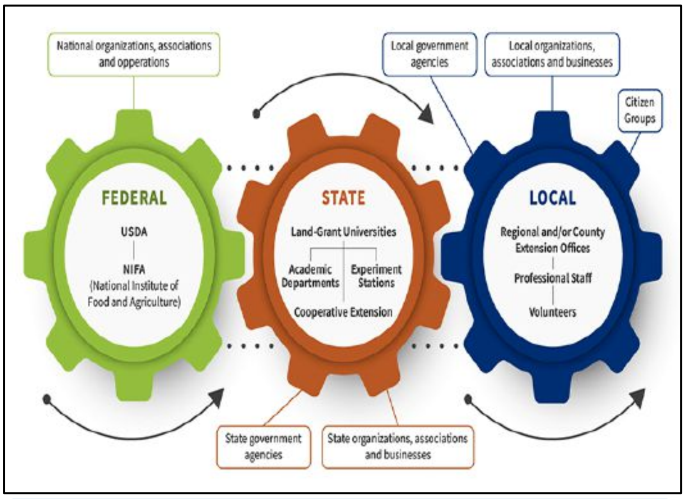
Private Extension in France

Extension services are offered in France by private sector companies and agricultural chambers. The chambers of agriculture are regarded as private organizations that rely on farmer dues for membership and services, although the French government provides sizable financing for operational and programme costs (Mondal, 2013)

Agricultural Extension Innovation in USA

Cooperative Extension System in USA

The National Institute of Food and Agriculture (NIFA), the National 4-H Council, and the Extension Foundation are working together with the Cooperative Extension System to translate research into action for agriculture, health, natural resources, and human sciences to quickly get useful tools and knowledge into the hands of people and communities who need them.



Source: (*Cooperative Extension System*, n.d.)

AGNIC IN USA

A network of public and private agricultural libraries and information centres called the Agricultural Network Information Centre (AgNIC) is connected over the internet and is managed by the National Agriculture Library (NAL) of the United States. Global access to agriculture is what the network intends to achieve. Access to a network of electronic sources on research and instruction in agriculture, food, natural resources, forestry, etc. is provided by the network through its website (Mondal, 2013)

4 H club in USA

The U.S. Department of Agriculture's (USDA) most successful youth development programme is 4-H. The 4-H (head-heart-hands-health) programme, which was originally known as "four-square education," aims to improve the quality of life by fostering positive youth development, facilitating learning, and involving young people in the work of their community. This is done through the Cooperative Extension Service. For more than a century, 4-H has been committed to providing young people with experiences that widen their skills and goals and foster their full potential. A 4-H club's goals are to encourage educational opportunities connected to the Land Grant University's body of knowledge and to give positive youth development chances to address young people's requirements for the Essential Elements of belonging, mastery, independence, and charity. All young people may join a 4-H club starting at age 8 or the fourth grade (the precise enrolment date is decided by the state), although participation is only permitted until the age of 21. Youth of any race, colour, creed, religion, national origin, sex, marital status, disability, or receiving government assistance are welcome to join 4-H Club. Source: (What Is a 4-H Club?, 2011).

Conclusion

Agricultural extension has developed into a diverse and dynamic field shaped by institutional innovation, technological change, and the need for more responsive service delivery. The cases reviewed in this paper show a clear transition from conventional top-down extension toward participatory, pluralistic, and demand-driven approaches. Models such as farmer field schools, participatory demonstration systems, public–private partnerships, farmer producer organizations, advisory call centres, expert systems, and specialized institutions such as KVKs and ATICs demonstrate different ways of improving the flow of knowledge between research systems and farming communities.

The review also shows that there is no single extension model that is universally applicable. The success of any innovation depends on the institutional context, the availability of technical and financial support, the nature of farmer demand, and the extent to which the system is inclusive of smallholders, women, and marginalized groups. In several countries, pluralistic arrangements that combine public, private, and community-based actors appear to offer the greatest flexibility and reach. At the same time, commercialization and cost-recovery approaches may limit access for resource-poor farmers unless they are supported by appropriate public safeguards.

Overall, the future of agricultural extension lies in systems that are locally adapted, institutionally coordinated, and technologically responsive. Strengthening farmer participation, improving staff capacity, and ensuring equitable access to information and services will be essential for making extension more effective, inclusive, and sustainable.

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Review

Cultivation of Pigeon Pea

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Abstract

Pigeon pea (*Cajanus cajan*) is an important legume crop widely grown in India and other tropical regions, valued for its high protein content (20–24%) and role in food and nutritional security. Commonly consumed as arhar or tur dal, it serves as a staple pulse in Indian diets. The crop improves soil fertility through biological nitrogen fixation and enhances soil structure by adding organic matter. Its deep root system provides drought tolerance, making it suitable for marginal and rainfed areas. Pigeon pea supports sustainable and eco-friendly farming systems and performs well in intercropping with cereals and oilseeds. Besides providing nutritious food for humans, it also supplies fodder for animals, while crop residues are used as fuel and fencing material. Economically, pigeon pea contributes significantly to farmers' income and rural employment. Overall, pigeon pea plays a vital role in sustainable agriculture, environmental health, and livelihood security.

Keywords: Nitrogen fixation, Soil fertility and Intercropping.

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Introduction

Pigeon pea (*Cajanus cajan* L.) is one of the most important grain legume crops of the tropics and subtropics, widely cultivated for its protein-rich seeds and multipurpose uses (Upadhyaya *et al.,* 2013). It belongs to the family Fabaceae (Leguminosae) and is commonly known as arhar, tur, or red gram in India, Congo pea or Angola pea in Africa, and yellow dhal in several Asian countries, while also serving as an important food and farm-support crop in many regions (Colorado State University, 2023; PROSEA, 1999). Pigeon pea occupies a prominent position among pulse crops due to its nutritional value, adaptability to diverse agro climatic conditions, and contribution to sustainable agriculture (ECHO Community, 2015). It is a major source of plant-based protein for millions of people, particularly in developing countries where animal protein is scarce or expensive.

India is the largest producer, consumer, and importer of pigeon pea, accounting for a substantial share of global production. The crop plays a vital role in ensuring food and nutritional security, especially for rural and low-income populations (Upadhyaya *et al.,* 2013. Pigeon pea seeds typically contain 20–24% protein along with essential amino acids, carbohydrates, vitamins, and minerals such as iron, calcium, and phosphorus. The split cotyledons (dal) are a staple component of daily diets in many parts of South Asia (Colorado State University, 2023). In addition to human consumption, pigeon pea residues such as leaves, husks, and broken grains are widely used as fodder for livestock, making it a valuable dual-purpose crop.

Botanically, pigeon pea is a deep-rooted perennial shrub that is usually cultivated as an annual crop. Plants grow to a height of about 1–4 meters, depending on genotype and growing conditions, and possess a woody stem with well-developed branches. The leaves are trifoliate, and the flowers are generally yellow with red or purple streaks. Pods are flat and slightly constricted, containing 2–9 seeds ECHO Community, 2015; PROSEA, 1999) that vary in size, shape, and color across varieties. The crop also shows substantial genetic diversity, which supports breeding and adaptation efforts (Kinhoégbè et al., 2022).

Pigeon pea is well adapted to marginal and rainfed areas where other crops often fail. It performs reasonably well under conditions of low fertility, limited rainfall, and high temperatures, making it particularly suitable for semi-arid tropics (Ariyo, 2000; Upadhyaya *et al.,* 2013).

Farmers frequently grow pigeon pea as an intercrop or mixed crop with cereals such as sorghum, pearl millet, maize, or rice, as well as with oilseeds and other legumes. Such intercropping systems help optimize land use, stabilize yields, suppress weeds, and reduce pest and disease incidence while providing diversified income sources (Mula & Saxena, 2010; Upadhyaya *et al.,* 2013).

Origin Place

Pigeon pea (*Cajanus cajan*) is believed to have originated in the Indian subcontinent, where it has been cultivated for more than 3,000 years. India is considered the primary center of origin and diversity, supported by the presence of wild relatives and wide genetic variability (Varshney et al., 2012). From India, the crop spread to East Africa, Southeast Asia, and later to the Americas through trade and migration (Ariyo, 2000; Upadhyaya et al., 2013). Today, pigeon pea is widely grown in tropical and subtropical regions of Asia, Africa, and Latin America. Its long history of cultivation in India highlights its importance as a traditional pulse crop and a major source of plant protein (Ariyo, 2000; Mula & Saxena, 2010).

Climate Requirement

Pigeon pea grows best under warm tropical to subtropical climates. It prefers:

- Temperature: 25˚C – 35˚C (warm weather).
- Rainfall: 600–1000 mm annually during early growth.
- Sunlight: Bright sunny weather during flowering and pod formation is ideal
- Photoperiod Pigeon pea is generally *short-day* sensitive, though varieties vary in photoperiod response. This combination of moderate moisture early on, warm temperatures, and dry conditions later makes pigeon pea ideal for semi-arid tropical regions where many other crops struggle.

Soil Requirement

However, it performs best in well-drained loamy to sandy loam soils rich in organic matter. Deep soils are preferred because the crop develops a strong taproot system that helps it tolerate drought by extracting moisture from lower layers. The ideal soil pH ranges from 6.0 to 7.5, although pigeon pea can tolerate slightly acidic to mildly alkaline conditions. Waterlogging is highly detrimental to the crop, as stagnant water promotes root diseases and poor nodulation. Heavy clay soils with poor drainage should therefore be avoided. Pigeon pea is moderately tolerant to low fertility and can grow on marginal lands, but balanced nutrient availability improves yield. Being a legume, it fixes atmospheric nitrogen, which enhances soil fertility. Proper land preparation and good soil structure support healthy root growth, nodulation, and overall crop productivity.

Land Preparation

Effective land preparation ensures good germination and plant establishment. Clear the field of existing weeds and crop residues. Plough deeply (about 20–30 cm) during the dry season to loosen the soil. Follow with 2–3 harrowings to create a fine, clod-free seedbed. Remove stones and level the land Deep tillage supports the crop's deep taproot system, helping it access moisture in deeper soil layers during dry periods.

Seed Selection and Treatment

Good seed selection is very important for getting a healthy pigeon pea crop. Always choose certified or improved seeds from a reliable source. Seeds should be clean, bold, mature, and free from diseases, insects, and damage. Avoid shriveled, broken, or discolored seeds. Select varieties that are suitable for your local climate and resistant to common pests and diseases. Before sowing, treat the seeds with fungicide or biofertilizer to protect them from soil-borne diseases and to improve germination. Using good quality seeds ensures better plant growth, higher yield, and uniform crop stand.

Sowing Time

Proper sowing time is very important for good growth and yield of pigeon pea. In India, pigeon pea is mainly sown with the onset of the monsoon during the Kharif season. The ideal sowing period is from mid-June to mid-July in most regions. In areas with early rains, sowing can start in early June, while in some southern states it may extend up to August. Timely sowing helps the crop use rainwater efficiently and escape severe pest and disease attack. Late sowing usually results in poor flowering and low yield. Therefore, farmers should sow pigeon pea at the recommended time for best results.

Method of Sowing

Spacing Proper spacing allows enough room for growth and sunlight.

Rainfed conditions 90–120 cm between rows and 30 cm between plants.

Irrigated fields 50–75 cm between rows and 15–20 cm between plants.

Depth sow seeda about 2.5 to 5 cm deep in the Soil.

Sowing Methods

Line sowing Most common and efficient.

Broadcasting For smaller plots or if row planting is difficult.

Intercropping Can be mixed with cereals like maize, sorghum, or millets.

Irrigation Management

Pigeon pea needs water mostly in the early stages and during flowering:

- Irrigate immediately after sowing if there's no rain.
- Maintain soil moisture for the first 6–8 weeks.
- After that, reduce the frequency; too much water during flowering reduces yield.
- Rainfall after flowers appear can affect pollination.

Fertilizer and Nutrient Management

Pigeon pea can fix nitrogen due to its association with Rhizobium bacteria, but a balanced fertilizer gives better yields as a legume, pigeon pea requires less nitrogen fertilizer due to its symbiotic relationship with Rhizobium. Still, soil test-based applications of phosphorus and potassium and addition of organic manure (FYM/compost) improve plant growth and yield.

- Apply organic manure or compost before planting.
- A basic fertilizer mix (e.g., NPK) helps early growth but should be based on soil test results.
- Too much nitrogen fertilizer isn't needed, as the plant fixes its own nitrogen.

Weed Management

Frequent weeding during early growth prevents competition for nutrients and water. Two to three intercultural operations (weeding + hoeing) are typically necessary before plants canopy the field and suppress weeds naturally. Perform 2–3 weedings/hoeing during early growth.

- Mechanical weeding or hand removal works well for small farms.

Good weed control ensures better stand and higher yield.

Pest and Disease Control

Common pests and diseases include:

- Pod borer (Helicoverpa armigera)
- Wilt and sterility mosaic disease

Control measures include:

- Crop rotation
- Use of resistant varieties
- Proper field sanitation
- Integrated pest management (IPM) practices.

Harvesting

Pigeon pea is ready to harvest when the pods turn brown and dry. This usually happens 120–180 days after planting, depending on the variety's maturity group.

Hand pick mature pods for high seed quality.

For larger fields, cuts can be made at base when plant segments are dry.

Post-Harvest and Storage

- Seeds should be dried to low moisture content (10–11%) before storage.
- Store in clean, dry jute bags or containers to avoid insect damage.

Importance of Pigeon Pea

- Major source of plant protein (20–24%) for human diet.
- Staple pulse crop in India (arhar/tur dal).
- Improves soil fertility by fixing atmospheric nitrogen.
- Suitable for marginal and rainfed areas.
- Deep roots help in drought tolerance.
- Used as food for humans and fodder for animals.
- Crop residues used as fuel and fencing material.
- Supports sustainable and eco-friendly farming.
- Provides income and employment to farmers.
- Useful in intercropping systems with cereals and oilseeds.
- Enhances soil structure and organic matter.
- Important for food and nutritional security.

Conclusion

Cultivation of pigeon pea (*Cajanus cajan*) plays a vital role in sustainable agriculture due to its adaptability to diverse soil and climatic conditions. The crop is well suited to rainfed and marginal areas, requires relatively low inputs, and improves soil fertility through biological nitrogen fixation. Its deep root system enhances drought tolerance, while intercropping with cereals and oilseeds increases land-use efficiency and farm income. Besides providing protein-rich food for humans, pigeon pea also supplies fodder and useful crop residues. With proper seed selection, timely sowing, balanced nutrient management, and effective pest control, farmers can achieve better yields and profitability. Overall, pigeon pea cultivation supports food security, environmental sustainability, and rural livelihoods, making it an important pulse crop for present and future farming systems.

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Review

Organic Waste Recycling for Soil Amendments : Advancing Circular Bioeconomy and Soil Health Restoration

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Abstract

The recycling of organic waste into soil supplements is an essential component of the circular bio economy, providing a long-term and regenerative solution to a range of environmental issues. With growing global worries about soil degradation, decreased agricultural output, and an increasing volume of organic waste, this technique offers a way to convert trash into a valuable resource. Organic resources such as food scraps, agricultural residues, animal manure, and green waste can be turned into nutrient-rich soil amendments by composting, vermicomposting, anaerobic digestion, or biochar synthesis. These additives improve soil structure, fertility, microbial diversity, and water-holding capacity, while also contributing significantly to carbon sequestration and climate change mitigation. This strategy not only decreases the need for chemical fertilizers, but it also diverts biodegradable trash from landfills, lowering methane emissions and contributing to a more sustainable waste management system. This closed-loop system, which is part of a circular bio economy, recycles biological resources, supports sustainable agriculture, and promotes local economic development by providing green jobs and lowering farmers' input costs. By incorporating organic waste recycling into agricultural and urban design, we can recover degraded soils, boost food security, and transition to a more resilient, low-carbon future. This strategy offers a comprehensive, scalable, and effective answer to sustainable land use and environmental regeneration.

Keywords: Soil Amendments, Organic Waste, Soil Fertility, Nutrient Recycling and Microbial Diversity

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Introduction

The term organic waste describes biodegradable materials derived from plants, animals, and other natural sources. Crop residues, weeds, straw, and husk are examples of agricultural materials; manure, bedding soaked in urine, and chicken litter are examples of animal wastes; leftover food, tea leaves, vegetable peels, and fruit trash are examples of kitchen scraps (Adegbeye *et al.*, 2020).

Along with agro-industrial wastes like press mud, bagasse, rice bran, and molasses, organic waste also includes items from gardens and landscapes such leaves, grass clippings, and small branches. Through the action of microbes, these wastes naturally break down into valuable organic materials. Organic waste can be a valuable resource for improving soil if it is properly managed and recycled.

It promotes microbial activity, improves soil structure, increases soil organic carbon, supplies vital nutrients, and fosters long-term soil fertility (Ahmad *et al.*, 2007). By transforming materials into nutrient-rich soil amendments that promote healthy plant growth and sustain ecological balance, recycling organic waste not only reduces environmental pollution and the load on landfills, but it also plays a critical role in sustainable agriculture (Biswas *et al.*, 2024).

Organic Waste as Soil Amendments

Recycling organic waste into soil amendments is essential for boosting sustainable agricultural systems, enhancing soil fertility, and restoring soil health (Scotti *et al.*, 2015). Crop residue, animal dung, kitchen litter, and agro-industrial byproducts are examples of organic waste that contribute useful organic matter to the soil, improving its chemical, biological, and physical characteristics. Humus, which is created when organic waste breaks down, increases aggregation, decreases bulk density, and enhances porosity, all of which lead to improved aeration, root penetration, and water infiltration (Ibrrahim *et al.*, 2016). Adding organic matter improves the soil's ability to retain water, increasing its resistance to drought and lowering the requirement for irrigation. Chemically derived organic amendments improve nutrient availability and decrease dependency on synthetic fertilizers by acting as a slow-release source of vital nutrients like nitrogen, phosphorus, potassium and micronutrients (Kumar *et al.*, 2025 & Pandey *et al.*, 2023a).

In terms of biology, recycled organic waste encourages the development of earthworms, beneficial bacteria, and other soil organisms which drive natural decomposition and nutrient cycling. These organisms help in the transformation of complicated organic compounds into forms that are easily absorbed by plants (Chatterjee *et al.*, 2017).

Additionally, using organic amendments promotes long-term ecological balance, increases soil resilience, and enhances soil biodiversity. Recycling organic waste also avoids environmental issues including greenhouse gas emissions, landfill buildup, and residue burning (Yoshida *et al.*, 2012). It lowers pollution, encourages the conversion of waste to resources, and supports a circular agricultural economy. Organic amendments also reduce the soil erosion, degradation, and fertility loss by increasing soil organic carbon. In general, adding organic waste to soil amendments is crucial for long-term agricultural sustainability, improving crop output, maintaining soil health, and protecting the environment (Singh *et al.*, 2022). In recent years, the idea of a circular bioeconomy is generated a lot of interest as a practical way to solve environmental problems and promote sustainable development. Recycling organic waste into beneficial assets that support economies and ecosystems is one of the main foundations of this approach. Converting organic waste into soil amendments is one of the most promising ways to use it. These amendments are essential for improving agricultural production, restoring soil health, and reducing climate change (Urra *et al.*, 2019).

Bio-Economy

An economic system focused on the sustainable production of food, energy, substances, and other products from biological resources such as plants, animals, microbes, and organic waste is known as the bioeconomy. The bioeconomy combines renewable biological resources and modern technologies like biotechnology, bioengineering, and bioprocessing to produce ecologically friendly solutions rather than depending on fossil fuels or non-renewable resources. Natural materials are effectively recycled and reused in a bioeconomy, which reduces waste, pollution, and promotes long-term ecological balance (Aguilar *et al.*, 2019). Biofuels, bioplastics, organic fertilizers, bio-based chemicals, compost made from organic waste, and biodegradable materials are a few examples of items from the bioeconomy (Yusuf *et al.*, 2024). Promoting sustainable development, lowering reliance on fossil fuels, saving natural ecosystems, and generating renewable employment are the objectives of the bioeconomy. In general, it promotes a circular system that ensures economic progress while protecting the environment through careful application and regeneration of biological resources.

The Circular Bioeconomy Concept

A circular bioeconomy ensures that organic resources are recycled and utilized instead of being thrown away by emphasizing the ongoing cycle of materials. A circular bioeconomy places more emphasis on sustainability, waste reduction, and the economical use of natural resources than the conventional linear economy, which adheres to a "take, make, dispose" approach. By using this strategy, organic waste can be reintegrated into the food chain, improving soil health, lowering carbon emissions, and producing goods with additional value for both rural and urban areas (Muscat *et al.*, 2021).

Bioeconomy Strategy and Its Relation to Soil

A national or international approach that encourages the sustainable use of biological resources- such as plants, microbes, animals, forests, and organic waste-to promote social well-being, economic growth, and environmental protection is known as a bioeconomy strategy. The strategy's main objectives are encouraging green technologies, replacing non-renewable resources with renewable bio-based materials, improve recycling systems, and advancing biotechnology, bioenergy, bioproducts, and sustainable agriculture. Because it is one of the most significant biological resources supporting food production, nutrient cycling, carbon storage, and ecosystem stability, soil is crucial to this framework. A robust bioeconomy strategy acknowledges that biomass production, biodiversity preservation, and the long-term viability of industrial and agricultural systems all depend on healthy soils. There is a close connection between soil and the bioeconomy. Crop growth, biofuel production, forestry support, and the production of other bio-based raw materials are all made possible by healthy soils (Yusuf & Ojedokun, 2024). A bioeconomy strategy encourages recycling organic waste, composting, the use of biofertilizers, conservation farming, and regenerative agriculture. These methods improve soil organic matter, nutrient availability, water-holding capacity, and microbial diversity (Prashar *et al*., 2025). These methods lessen the need for chemical fertilizers, improve soil carbon sequestration, and lessen soil degradation all of which contribute to the mitigation of climate change. Additionally, the policy promotes the use of bio-based goods, such as bioplastics and bioenergy, which lessen pollution of the environment and soil ecosystems. By encouraging sustainable land management, recycling biological resources, restoring degraded lands, and increasing soil biodiversity, the bioeconomy strategy improves soil health (Anikwe & Ife., 2023). Thus, a steady supply of biomass, food security, environmental resilience, and long-term economic gains are all guaranteed by healthy soils. Because soil sustains the bioeconomy and the bioeconomy strengthens soils for future generations, the relationship is circular and mutually beneficial.

Need to Convert Organic Waste into Soil Amendments

The need to transform organic waste into soil supplements originates from the increasing issues of soil degradation, decreased soil fertility, environmental contamination, and higher demands on agricultural systems. Organic waste, including agricultural residues, livestock manure, food scraps, and agro-industrial byproducts, is generated in vast quantities, and if not properly managed, it leads to landfill accumulation, greenhouse gas emissions, unpleasant odors, and water contamination. Instead of allowing this trash to become an environmental burden, recycling it into soil amendments supports soil health and sustainable agriculture. Organic amendments improve soil structure, boost organic carbon, increase water retention, and promote nutrient cycling (Tiwari *et al*., 2024). They provide critical nutrients in a slow-release manner, increasing soil fertility without relying on synthetic fertilizers (Alvarenga *et al*., 2017). Converting organic waste into compost, vermicompost, biofertilizers, or biochar increases microbial diversity and soil biological activity, which is essential for good plant growth (Kumar et al., 2025). This recycling process additionally conforms to the ideas of a circular economy, in which waste is converted into a valuable resource while decreasing pollution and protecting natural habitats. As a result, turning organic waste to soil amendments is critical not just for sustainable agriculture, but also for protecting the environment, climatic resilience, and long-term soil productivity (Masullo *et al*., 2017).

Impact of Organic Waste on Soil Health

Improvement of Soil Fertility

Soil fertility improvement is critical for long-term agricultural productivity and crop production durability (Shang *et al*., 2014). Organic waste, when turned into soil amendments, offers vital nutrients, including nitrogen, phosphorus, potassium, and micronutrients in a slow-release form, assuring a consistent supply for plants. Organic matter boosts soil organic carbon, increases cation exchange capacity, and improves nutrient retention (Kumar & Pathak, 2025). This reduces nitrogen losses owing to leaching while increasing fertilizer efficiency. Organic amendments also help to build humus, which enriches the soil and increases its buffering ability. As a result, plants thrive, yields rise, and the soil remains productive for future cropping seasons (Hiranmai *et al*., 2024 & Pal *et al.*, 2025).

Enhancement of Soil Biological Activity

Boosting soil biological activity serves as essential for a healthy and functional soil environment. When organic waste is recycled into soil amendments, it delivers nourishment to beneficial living things like bacteria, fungus, actinomycetes, and earthworms (Chatterjee *et al*., 2017). These organisms use natural processes to decompose organic materials, release nutrients, and enhance soil structure. Their activities promote nutrient cycling, humus formation, and disease suppression by competing with dangerous pathogens. Increased microbial diversity improves soil resilience and increases plant development (Pedrinho *et al.*, 2024). Active soil life also aids in residue decomposition, which improves soil aeration and aggregation. Overall, increased biological activity promotes soil health and productivity (Pandey *et al.*, 2023b).

Minimize the Dependency of Chemical Fertilizers

By delivering a sustainable and natural supply of nutrients, turning organic waste into soil amendments significantly reduces the need for synthetic nutrients. By releasing nutrients gradually, organic materials ensure long-term availability and minimize the frequency of fertilizer treatments (Kumar *et al.*, 2025). In addition to saving farmers money on inputs, this reduces the possibility of nutrient imbalances and soil deterioration brought on by overuse of chemicals. Reduced reliance on artificial fertilizers avoids salinity, acidity, and the loss of helpful microbes in the soil. Additionally, it reduces pollution in the environment, supports integrated nutrient management, and advances environmentally friendly farming methods (Kumar & Pathak, 2025). Ultimately, while preserving soil productivity, organic additions promote sustainable agriculture (Ansari *et al.*, 2019).

Environmental Protection

As reducing pollution and preserving natural resources, recycling organic waste into soil supplements is essential to environmental protection. Composting and vermicomposting turn trash into useful inputs instead of burning crop residues or disposing of organic waste in landfills (Singh *et al.*, 2011). This reduces groundwater contamination, unpleasant odors, and greenhouse gas emissions. By enhancing soil carbon sequestration, organic amendments help slow down global warming and repair degraded areas (Sachan *et al.*, 2024). Additionally, they lessen the use of chemical fertilizers, which stops dangerous materials from running off into rivers and lakes. Organic waste recycling promotes a cleaner environment and better ecosystems by lowering trash creation and encouraging natural nutrient cycling (Singh *et al.*, 2024).

Improved Soil Structure and Water-Holding Capacity

Soil structure and moisture retention are significantly enhanced by organic fertilizers made from recovered trash. Organic matter increases porosity and decreases compaction by binding soil particles into stable aggregates (Kumar *et al.*, 2024). Aeration, microbiological activity, and root penetration are all improved by improved soil structure. Additionally, better aggregation lessens surface crusting and erosion. The soil's ability to keep water is increased by organic components acting as sponges, which is crucial during dry spells. This lessens the need for watering and gives plants access to moisture for longer periods of time. Organic amendments make soil more resilient and productive by improving both structure and moisture balance (Singh *et al.*, 2023).

Promotion of Circular Economy

By transforming waste into a useful resource, the circular economy is greatly supported by the conversion of organic waste into soil supplements. Recycling techniques including composting, vermicomposting, and biochar synthesis restore nutrients to the soil rather than burning or disposing of organic matter in landfills. This lessens reliance on outside inputs and closes the nutrition loop. A circular system encourages sustainable farming methods, reduces waste, and preserves natural resources. It promotes green jobs, lessens pollution in the environment, and improves ecological equilibrium. The circular economy enhances food systems, safeguards the environment, and fosters long-term sustainability by guaranteeing the ongoing reuse of biological elements (Alonso *et al.*, 2020).

Common Organic Waste Recycling Methods

There are several methods to recycle organic waste into soil amendments, each with its unique benefits:

Composting

Composting is an environmentally responsible way to improve soil fertility since it encourages sustainable agriculture and reduces reliance on chemical fertilizers by recycling organic materials. In the natural biological process of composting, microorganisms like bacteria and fungi convert organic waste-such as crop leftovers, kitchen scraps, leaves, and animal manure-into humus that is rich in nutrients (Bashi *et al.*, 2025). In order to sustain microbial activity, this process needs sufficient oxygen, moisture, and temperature. In addition to decreasing waste volume, effectively managed composting turns it into a stable soil supplement that is high in vital nutrients like potassium, phosphate, and nitrogen. Compost boosts microbial activity, strengthens the soil's ability to hold water, and helps prevent plant diseases. Additionally, it helps reduce greenhouse gas emissions by sequestering carbon (Odlare *et al.*, 2011).

Vermicomposting

Earthworms, typically species like *Eisenia fetida* or *Eudrilus eugeniae*, are used in vermicomposting to break down organic waste into fine, nutrient-rich vermicast. Compared to conventional compost, earthworms' castings have a better nutrient availability since they eat organic matter. Vermicompost is an excellent organic fertilizer because it is full of helpful microorganisms, enzymes, and compounds that promote plant growth (Lim *et al.*, 2015 & Kumar et al., 2024). Worm survival is favoured by this mechanism, which functions best in damp, dark, and aerated environments. Vermicomposting stimulates soil biological activity, root development, nutrient cycling, and soil aeration(Kumar *et al.*, 2024 and Kumar *et al.*, 2025). Additionally, it offers quicker decomposition than traditional composting. Vermicomposting is commonly used by farmers to effectively manage farm waste and create a useful amendment that enhances crop output and soil health in a sustainable manner (Kumar *et al.*, 2025).

Biochar Production

Pyrolysis is a method that produces biochar by heating biomass, such as wood chips, crop leftovers, or manure, in the absence or almost absence of oxygen. While doing this, organic matter is transformed into biochar, a stable solid that is rich in carbon. Biochar improves soil structure, boosts water-holding capacity, and improves nutrient retention (Fu *et al.*, 2019). Its porous nature fosters the biological health of the soil by providing dwellings for helpful microorganisms (Khan *et al.*, 2024), Additionally, biochar helps lessen nutrient leaching and can increase fertilizer effectiveness. It is a useful technique for mitigating climate change because, crucially, it keeps carbon in a stable state for hundreds to thousands of years (Alkharabsheh *et al.*, 2021). Biochar is produce using waste biomass, which promotes trash recycling and sustainable agriculture.

Liquid Fertilizer Production

The process of creating nutrient-rich liquid formulations from organic materials like compost, plant wastes, animal manure, and kitchen trash is known as liquid fertilizer. Fermentation, aerobic digestion, and nutrient extraction from vermicompost or compost are common techniques (Kalita *et al.*, 2025). Nutrients including nitrogen, potassium, micronutrients, amino acids, and compounds that promote plant growth are easily accessible when using liquid fertilizers. They are simple to administer using drip irrigation or foliar sprays, guaranteeing rapid nutrient absorption and enhanced plant growth. Liquid organic fertilizers promote microbial activity, improve root development, and quickly address vitamin deficiencies (Varshini & Jayanthi, 2020). They help lessen reliance on chemical fertilizers and are inexpensive to grow on farms. This technique recycles trash into useful inputs for crop production, enhances nutrient-use efficiency, and promotes sustainable agriculture (Brichi *et al.*, 2023).

Environmental and Economic Benefits of Recycling Organic Waste

Organic waste recycling has several economic and environmental benefits that promote resource-efficient development, healthy ecosystems, and sustainable agriculture. Large amounts of biodegradable waste are kept out of landfills by recycling techniques like composting, vermicomposting, anaerobic digestion, and biochar synthesis (Sharma *et al.*, 2019). Methane, a major greenhouse gas that contributes to climate change, is produced when organic waste breaks down in landfills (Kiehbadroudinezhad *et al.*, 2024).

Methane emissions are greatly decreased by treating the waste using specified techniques. Recycling organic matter also improves soil structure, water-holding capacity, and aeration by adding stable carbon to the soil (Bashir *et al.*, 2021). This promotes the growth of roots and strengthens the soil's resistance to drought and heavy precipitation. In addition to increasing beneficial microbial activity and decreasing the demand for chemical fertilizers, the return of organic matter also lowers soil and water pollution (Dixit *et al.*, 2024). Compost, vermicompost, liquid fertilizers, fermented matter, and biochar are just a few of the valuable products that may be produced economically by recycling organic waste (Dey *et al.*, 2026). These products increase long-term soil production and lessen farmers' dependency on expensive synthetic fertilizers. Additionally, anaerobic digestion systems produce biogas, which can be utilized for heating, cooking, or the generation of power, providing extra revenue or savings. Organic amendments are produced and sold locally, boosting rural economies and generating jobs (Masullo, 2017). Organic waste recycling promotes resource efficiency and lowers waste disposal costs, which helps farmers, communities, and the environment (Matisic *et al.*, 2024).

Some crucial actions must be done to fully exploit the potential of recycling organic waste for soil restoration:

1. ***Infrastructure Development:*** Both urban and rural areas need to have efficient waste collection, sorting, and processing systems. This entails establishing facilities specifically for composting and encouraging localized recycling initiatives.
2. ***Policy Support and Subsidies:*** By establishing laws that promote sustainable waste management techniques and provide benefits for the recycling of organic waste, governments can play a significant role. This can involve requiring the diversion of organic waste from landfills or providing incentives for composting companies.
3. ***Public Education and Awareness:*** Educating the public about the advantages of recycling organic waste and applying soil amendments is essential for fostering community involvement. Educational initiatives can encourage businesses and individuals to take initiative, cutting waste and promoting sustainable local agriculture.
4. ***Cooperation Between Sectors:*** To promote innovation and investment in organic waste recycling technologies, cooperation between governments, corporations, non-governmental organizations, and local communities is essential. We can build a more effective and long-lasting circular bioeconomy by coordinating our efforts.

Conclusion

A key element of the circular bioeconomy, recycling organic waste into soil amendments has significant beneficial impacts on the environment and the economy. This method turns trash into a useful resource by turning materials like crop leftovers, food waste, and animal manure into valuable products like compost, vermicompost, biochar, and microbial digestate. These additives contribute to healthier and more resilient soils by increasing microbial activity, improving soil fertility, and improving nutrient availability. Higher agricultural yields are supported by healthier soils, which also reduce the demand for artificial fertilizers, saving farmers money and reducing pollution. In terms of the environment, recycling organic waste maintains a lot of biodegradable materials out of waste dumps, in which they normally emit the powerful greenhouse gas methane. alternative methods like the creation of biochar and composting aid in the sequestration of carbon, which helps to mitigate climate change. By enhancing soil structure, boosting water-holding capacity, and promoting biodiversity, this technique also increases ecosystem resilience.

Economically speaking, turning compost into useful soil inputs lowers waste management costs, generates new revenue streams, and encourages sustainable farming methods. Recycling organic waste will be essential to promoting circular economies, lowering environmental pressures, and promoting long-term sustainability in food production as societies move toward greener and more resource-efficient systems.

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Review

Livestock and Allied Disciplines in Sustainable Agriculture

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Abstract

Livestock and allied agricultural enterprises constitute an essential component of sustainable farming systems by enhancing resource efficiency, ecological balance, and farm profitability. The integration of livestock with crop production promotes circular nutrient flows, where crop residues are utilized as animal feed and animal manure enriches soil fertility. Such interactions reduce dependency on synthetic fertilizers, lower production costs and improve soil health. Sustainable livestock management further emphasizes balanced feeding, pasture-based grazing, preventive healthcare, animal welfare and scientific manure handling to minimize environmental impacts while maintaining productivity. Allied sectors including dairy farming, poultry rearing, small ruminant production, fisheries and apiculture diversify income sources, generate year-round employment and strengthen household food and nutritional security. These enterprises utilize locally available resources and agricultural by-products, contributing to waste reduction and enhanced farm resilience. Moreover, climate-smart practices such as biogas production, carbon sequestration through grasslands and efficient feed utilization help mitigate greenhouse gas emissions associated with livestock systems. By combining traditional knowledge with modern innovations and supportive policies, livestock-centered integrated farming systems offer a sustainable pathway for improving livelihoods, conserving natural resources and ensuring long-term agricultural stability. Thus, livestock and allied disciplines are not merely supplementary activities but foundational pillars of sustainable agriculture and rural development.

Keywords: Sustainable agriculture, Livestock integration, Crop–livestock systems, Resource-use efficiency, Agro-ecosystem resilience.

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Introduction

Livestock has always been an integral component of agricultural systems rather than a separate enterprise (Herrero et al., 2013; Seré & Steinfeld, 1996). In traditional farming landscapes, crops, animals, trees, fisheries and other allied activities functioned together in a mutually supportive cycle where the waste of one component became the resource of another (FAO, 2024; Robinson et al., 2011). Over time, specialization and industrialization separated livestock from cropping systems, leading to excessive input use, nutrient imbalances, environmental degradation and rising production costs (Lemaire et al., 2014; Herrero et al., 2013). Sustainable agriculture seeks to restore this lost integration by repositioning livestock and allied disciplines as essential pillars of ecological balance, farm profitability and rural livelihoods (FAO, 2024; Thornton & Herrero, 2015).

This chapter discusses how scientifically managed livestock production, when combined with allied sectors such as dairy, poultry, fisheries, apiculture, and waste recycling, contributes to resilient, low-input, and climate-smart agricultural systems (Foley et al., 2011; Thornton & Herrero, 2015). The emphasis is on approaches that conserve natural resources, enhance animal welfare, reduce environmental footprints and generate diversified income for farmers (Mottet et al., 2017; Robinson et al., 2011).

Role of Livestock in Sustainable Farming Systems

Livestock contributes to sustainability through multiple pathways (Herrero et al., 2013). Animals convert crop residues, grasses, and by-products that are unsuitable for human consumption into milk, meat, eggs, fiber, and manure, improving resource-use efficiency and minimizing waste (Mottet et al., 2017; Seré & Steinfeld, 1996). In addition, livestock provides draft power, organic manure and regular income, all of which help stabilize smallholder farming systems (Thornton & Herrero, 2015).

From a socioeconomic perspective, livestock acts as a living asset or “**mobile bank**” for farmers, since animals can be sold during emergencies and reduce vulnerability to crop failure or market fluctuations (Randolph et al., 2007; Thornton & Herrero, 2015). Nutritionally, animal products supply high-quality proteins, vitamins and minerals, thereby improving household food security and dietary quality (Herrero et al., 2013; Randolph et al., 2007). Ecologically, well-managed livestock supports nutrient cycling because manure enriches soil organic matter, enhances microbial activity and improves soil structure (Lemaire et al., 2014; FAO, 2024).

Integration of Crops and Livestock

Integrated crop-livestock systems form the backbone of sustainable agriculture because crops and animals are managed together rather than independently (Lemaire et al., 2014; Robinson et al., 2011). In such systems, crop residues such as straw, stover, husks and bran serve as feed, while animal manure returns nutrients to the soil, reducing dependence on external inputs (Mottet et al., 2017; FAO, 2024). These systems improve nutrient recycling, increase overall farm productivity, and strengthen resilience under climate stress (Herrero et al., 2013; Thornton & Herrero, 2015). When properly managed, integration reduces losses, supports soil health, and creates more diversified and stable farm income (Lemaire et al., 2014; Mottet et al., 2017).

This integration provides several advantages

- Reduced dependence on synthetic fertilizers
- Improved soil fertility and water retention
- Lower feed costs
- Diversified farm income
- Enhanced resilience to climatic variability

For example, after harvesting cereals, livestock can graze crop stubbles, which helps control weeds while providing feed. Similarly, green fodder crops can be included in rotations to restore soil nitrogen and supply balanced nutrition to animals. Such circular resource use reduces both waste and production costs.

Sustainable Feeding and Nutrition Management

Feed production accounts for a large portion of livestock related environmental impacts. Therefore, sustainable feeding strategies aim to maximize local resources and minimize external inputs. The use of crop residues, agro industrial by-products and fodder trees reduces pressure on cultivated land.

Key practices include

- Cultivation of perennial fodders and legumes
- Silage and hay preparation for lean seasons
- Use of multi nutrient blocks and mineral mixtures
- Incorporation of tree leaves and shrubs in diets
- Precision feeding based on animal requirements

Balanced nutrition improves feed conversion efficiency, reduces methane emissions per unit of product, and enhances animal health. Feeding animals only what they require prevents wastage and lowers costs. Moreover, indigenous breeds adapted to local feeds often perform better under low input systems than high producing exotic breeds that demand costly concentrate feeds.

Pasture Based and Grazing Systems

Grazing systems play a crucial role in sustainable livestock management. Properly managed pastures reduce feed costs, conserve soil and enhance biodiversity. Rotational grazing, where animals are moved between paddocks, prevents overgrazing and allows vegetation to regenerate.

Benefits of pasture-based systems include

- Improved soil organic carbon through root biomass
- Reduced soil erosion
- Better water infiltration
- Lower dependence on purchased feed
- Enhanced animal welfare

Grasslands also act as carbon sinks, contributing to climate change mitigation. Mixed pastures containing grasses and legumes improve protein content and reduce the need for synthetic nitrogen fertilizers. When animals graze naturally, their behavior and health improve, reducing stress related diseases.

Animal Health and Welfare

Healthy animals are more productive and require fewer chemical inputs such as antibiotics and synthetic drugs. Sustainable livestock production emphasizes preventive healthcare rather than curative treatments. Biosecurity, vaccination, hygiene and balanced nutrition are fundamental.

Important measures include

- Clean housing with proper ventilation
- Access to clean water
- Regular health monitoring
- Vaccination and deworming schedules
- Stress free handling

Ethical treatment of animals is increasingly recognized as both a moral responsibility and a production necessity. Stress reduces immunity and productivity, leading to economic losses. Welfare friendly practices ensure better growth, reproduction and product quality while meeting consumer expectations for ethically produced food.

Manure Management and Nutrient Recycling

Animal waste, if mismanaged, becomes an environmental pollutant. However, when properly treated, manure is a valuable resource. Sustainable manure management transforms waste into fertilizer and energy, closing the nutrient loop.

Practices include

- Composting
- Vermicomposting
- Biogas production
- Slurry application through fertigation

Composted manure improves soil structure, increases water holding capacity, and enhances microbial diversity. Biogas plants convert dung into renewable energy for cooking and lighting, while the slurry serves as a nutrient rich fertilizer. Such systems reduce reliance on fossil fuels and chemical fertilizers, lowering both costs and emissions.

Dairy Farming in Sustainable Agriculture

Dairy farming provides regular cash flow and nutritional security. Sustainable dairy systems prioritize indigenous breeds, balanced feeding, hygienic milk production and efficient waste management. Small scale dairying integrated with crop farming allows farmers to utilize crop residues effectively while supplying manure for fields. Low input dairying reduces feed and medicine costs while ensuring stable returns. Value addition through processing into curd, butter and cheese increases profitability. Cooperative models enable small farmers to access markets, technical support and fair pricing.

Poultry and Small Ruminants

Poultry, goats and sheep are well suited to smallholder systems because they require limited space and investment. Backyard poultry provides eggs and meat with minimal inputs. Local breeds are hardy and resistant to diseases. Small ruminants convert shrubs and weeds into valuable products, making them ideal for marginal lands. Their quick reproduction cycles offer rapid income generation. Integrating these animals diversifies production and spreads economic risk.

Fisheries, Apiculture and Allied Enterprises

Allied disciplines complement livestock and crop production. Fish farming in farm ponds improves water use efficiency while providing protein rich food. Integrated fish–duck or fish–poultry systems recycle nutrients naturally. Apiculture enhances pollination, increasing crop yields and biodiversity. Honey and wax provide additional income. Mushroom cultivation, sericulture and vermiculture also utilize agricultural waste, promoting resource recycling and entrepreneurship. Such diversification strengthens farm resilience and creates year-round employment opportunities.

Climate Change and Environmental Considerations

Livestock production is often criticized for greenhouse gas emissions. Sustainable approaches address this issue through improved feed efficiency, manure management and pasture restoration. Reducing methane emissions through better nutrition and adopting biogas systems significantly lowers the carbon footprint.

Carbon sequestration through grasslands and agroforestry further offsets emissions. Integrating trees with livestock provides shade, improves microclimates, enhances biodiversity and climate also impact on living organism (Rana et al., 2017). Climate resilient breeds that tolerate heat and diseases are also crucial for future sustainability.

Socioeconomic and Policy Dimensions

Livestock supports livelihoods, particularly for women and small farmers. Policies that promote access to veterinary services, credit, insurance and markets are essential. Capacity building through training and extension services enhances knowledge adoption.

Farmer cooperatives and producer organizations strengthen bargaining power and facilitate collective marketing. Government incentives for biogas, organic manure and pasture development encourage sustainable practices at scale.

Future Prospects

The future of sustainable livestock lies in combining traditional wisdom with modern innovations. Digital tools such as mobile based advisory services, precision feeding systems, and health monitoring sensors can improve efficiency.

At the same time, local breeds and ecological principles must be preserved. A holistic approach that integrates livestock with crops, trees and allied enterprises will ensure food security, environmental protection and economic stability. Livestock should not be viewed merely as production units but as dynamic components of agroecosystems.

Conclusion

Livestock and allied disciplines are central to sustainable agriculture. When integrated thoughtfully, animals contribute to nutrient recycling, soil health, income diversification and resilience against climate and market risks. Sustainable feeding, grazing, healthcare and waste management practices minimize environmental impacts while enhancing productivity. Allied activities such as dairy, poultry, fisheries and apiculture further strengthen farm sustainability. Thus, livestock-based systems that respect ecological limits, animal welfare, and farmer livelihoods represent a pathway toward truly sustainable agricultural development. By adopting integrated, resource efficient and climate smart strategies, farmers can achieve productivity without compromising environmental integrity or future generations.

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Review

Scaling Climate-Smart Agriculture for Resilient Farming

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Abstract

Climate change poses a major threat to global agriculture and food security due to rising temperatures, erratic rainfall, droughts, floods and increased pest pressure, particularly affecting the farming systems of smallholder farmers. The global population is projected to reach 9.7 billion by 2050. Sustainable methods are needed to increase food production while conserving natural resources. Climate-Smart Agriculture (CSA) integrates three objectives: increasing agricultural productivity, enhancing resilience and adaptability to climate change, and reducing greenhouse gas emissions. This review examines the key factors influencing the adoption of CSA, including household characteristics, farm size, land ownership, and access to extension services, credit, markets and farmer organizations. It also compiles evidence regarding the impact of CSA on crop yields, farm income, climate resilience and environmental sustainability. Furthermore, the review emphasizes policy strategies for scaling up CSA through improved extension systems, climate finance, digital advisory services, and context-specific institutional support for sustainable agricultural development.

Keywords: Climate-Smart Agriculture (CSA), environmental sustainability, Temperature, Rainfall and Farming System.

Introduction

Agriculture is deeply linked to weather and climate, accounting for approximately 20% of global greenhouse gas emissions (Rana, *et.al.,* 2017; Kang *et al.,* 2019). Rising temperatures, erratic rainfall, and extreme weather events are reducing crop yields, pest infestation and destabilizing supply chains (Lobell et al., 2014). By 2050, 70% more food will be required to feed a population of 9.7 billion (United Nations, 2021). Since increasing production through conventional methods risks resource depletion, there is a need for climate-resilient practices.

Climate-Smart Agriculture (CSA) offers one such pathway. According to the FAO, it entails transforming agri-food systems to enhance productivity, improve resilience, and reduce emissions (FAO 2013). CSA is not a single technique but a suite of practices, including drought-tolerant crop varieties, water-saving irrigation, conservation agriculture, agroforestry, and improved livestock management (Vermeulen *et al.* 2012).

Despite policy interest, its adoption remains limited. Understanding its determinants and impacts is essential for effective scaling up. This review synthesizes evidence to identify the barriers to and opportunities for the adoption of CSA among smallholder farmers.

Determinants of CSA Adoption

Adoption is a multi-stage decision influenced by household, farm, and institutional factors.

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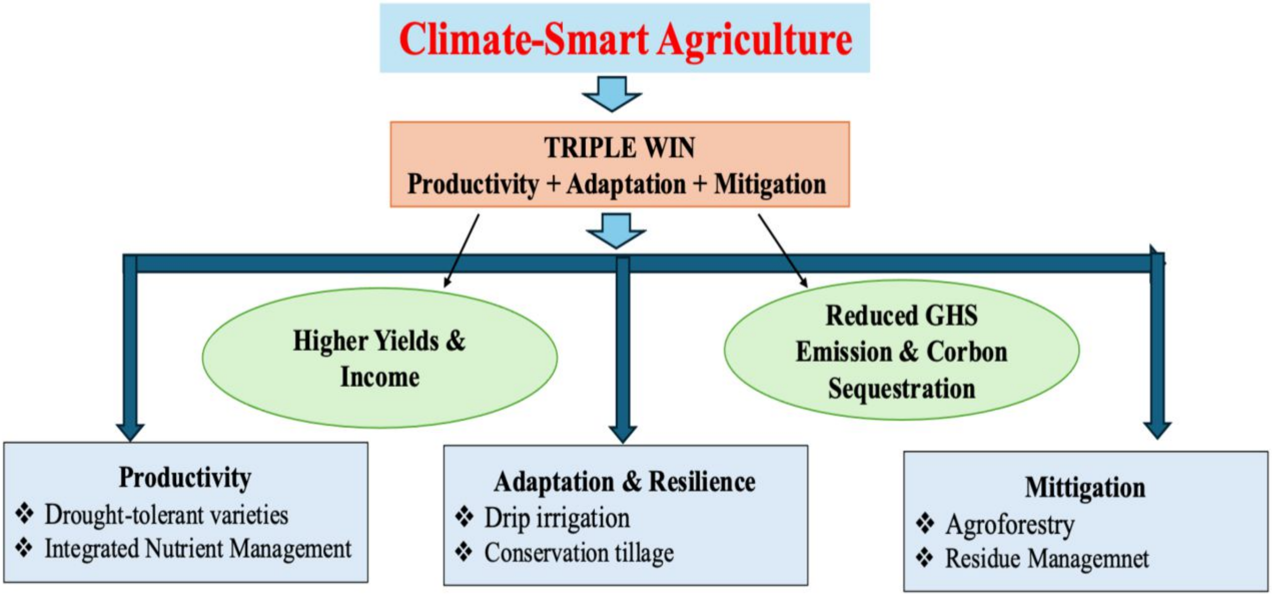

Figure 1: The three pillars of climate-smart agriculture and their overlap for achieving triple wins

Household and farmer characteristics

Age, education, gender, and risk preference influence the adoption of CSA. Older farmers tend to plan for shorter time horizons, resulting in lower adoption rates. Education enhances the capacity to understand climate-related risks and technical information (Li *et. al.* 2024). Women farmers face greater challenges in accessing land, credit, and extension services; consequently, despite being more vulnerable to climate impacts, they are less able to adopt these practices (Porter *et al.* 2014). Farmers who are risk-averse tend to avoid adopting technologies that entail high initial costs and uncertain returns, such as improved seeds or drip irrigation.

While income from non-farm sources provides the capacity to invest, it can also divert labor away from farming activities, potentially leading to reduced adoption of labor-intensive practices—such as crop residue management.

Farm and biophysical conditions: Farm size, fragmentation, and land tenure security influence investment incentives. Small landholdings limit economies of scale for mechanized agricultural practices, such as laser land leveling. Secure land tenure encourages long-term investment in soil conservation and agroforestry, whereas insecure tenure discourages such investments (Thornton *et al.* 2014).

Stress-tolerant varieties are adopted due to agro-ecological stress, but severe resource constraints can hinder their use. Soil degradation and water scarcity act as both 'push' and 'pull' factors (Howden et al., 2007).

Institutional and market access: Extension services help bridge the information gap regarding climate risks and CSA options. However, their reach is limited, and the advice provided is often generic. Access to credit for purchasing inputs and equipment is crucial. Informal credit is expensive and discourages investment (Khatri-Chhetri et al., 2017).

Membership in cooperatives and farmer groups reduces costs associated with inputs, marketing, and information sharing. Social networks and the examples set by peers significantly influence adoption decisions (Ma & Rahut 2024).

Table 1. Key Factors Affecting Climate-Smart Agriculture (CSA) Adoption by Smallholder Farmers

Category	Factors	Impact on CSA Adoption
Household Characteristics	Age, education, gender, risk preference	Higher education promotes adoption, whereas older and risk-averse farmers tend to adopt fewer CSA practices
Farm Characteristics	Farm size, land tenure security, soil quality, water availability	Secure land tenure and larger farms encourage long-term investment in CSA technologies
Institutional Access	Extension services, credit availability, market access, climate information	Better access to information, finance and markets significantly increases adoption
Social Factors	Farmer organizations, cooperatives, peer networks and social learning	Membership in groups and farmer-to-farmer knowledge exchange enhances CSA uptake

Biophysical and Socioeconomic Impacts of CSA

CSA delivers benefits across productivity, resilience, and mitigation pillars.

Productivity and income: Conservation agriculture and integrated soil fertility management improve soil moisture and nutrient use efficiency, thereby increasing yields. In South Asia, adopting crop rotations that include pulse crops reduced input costs and increased both paddy yields and net profits. In sub-Saharan Africa, drought-tolerant maize varieties maintained stable yields despite erratic rainfall (Burney *et al.* 2010). Yield benefits depend on complementary inputs. Without adequate nutrients and water, stress-tolerant seeds show limited gains (Lobell *et al.* 2014).

Adaptation and resilience: Water-saving techniques such as drip irrigation and raised beds reduce water stress in crops during droughts (Porter et al., 2014). Conservation agriculture improves soil structure, thereby increasing water absorption capacity and providing protection against both drought and heavy rainfall. For livestock, feeding with fodder trees in a climate-smart manner and improving fodder storage helps maintain nutritional levels even during periods of feed scarcity (Thornton *et al.* 2014). Integrating intercropping (growing multiple crops simultaneously) with mixed crop-livestock farming spreads risk and stabilizes income despite climate-related shocks (Vermeulen *et al.* 2012).

Mitigation co-benefits: CSA reduces emissions per unit of production. Conservation agriculture, which retains crop residues in the field, builds up organic carbon in the soil over time. Precision nutrient management reduces the excessive use of nitrogen, thereby lowering N_2O emissions (Burney *et al.* 2010).

Agroforestry sequesters carbon in biomass while also providing microclimate-related benefits. However, the carbon mitigation benefit is often viewed as an additional advantage; farmers prioritize productivity and risk reduction (FAO 2013).

Table 2. Major Impacts of Climate-Smart Agriculture Practices

CSA Pillar	Examples of Practices	Major Benefits/Impacts
Productivity	Drought-tolerant varieties, integrated nutrient management, improved crop management	Higher and more stable crop yields, improved farm income and resource-use efficiency
Adaptation and Resilience	Drip irrigation, conservation agriculture, crop diversification, water harvesting	Reduced drought and flood risks, improved soil health and greater climate resilience
Mitigation	Agroforestry, residue retention, precision nutrient management, soil carbon management	Carbon sequestration, reduced greenhouse gas emissions and improved environmental sustainability

Policy Pathways for Scaling CSA

Evidence points to four priority areas for policy (Ma & Rahut 2024).

Extension and advisory services: Extension services should disseminate information related to weather and CSA (Climate-Smart Agriculture) using local languages and methods. Digital platforms, mobile apps, and ICT-based advisories enable reaching a larger audience at a low cost (Li *et al.* 2024). Integrating these with farmer field schools and demonstration plots is essential to build trust and enhance skills.

Training extension agents on climate science and CSA is essential. Climate modules should be integrated into agricultural education.

Finance and input access: There is a need for specially designed financial products, such as credit for CSA investments, index-based insurance, and targeted subsidies for the transition period (Khatri-Chhetri et al., 2017). Public-private partnerships can strengthen supply chains for drought-tolerant seeds and improved irrigation equipmen.

Farmer organizations and social learning: Cooperative societies aggregate the demand for inputs, negotiate prices, and facilitate collective learning (Porter *et al.* 2014). Policy should support the formation of groups and the enhancement of their capacities, particularly for women and marginalized farmers (Ma and Rahut 2024).

Context-specific integration: No single CSA package is suitable for all situations. Policies must be tailored to agro-ecology, market access, and farmers' resources (Howden et al., 2007). Aligning with social protection, nutrition programs, and rural infrastructure improves adoption rates and impact.

Research Gaps and Future Directions

There have been few studies to date on the long-term impacts of CSA on soil health, farm income, and landscape-level outcomes (Lobell et al., 2014). Cost-benefit analyses across diverse climatic conditions are needed (Burney et al., 2010).

Decision-support tools tailored to local conditions can assist farmers in selecting the optimal combination of CSA practices (Vermeulen et al., 2012). Innovations in financing, such as carbon credits for soil carbon sequestration, require testing.

International collaboration and technology transfer are crucial for equitable CSA diffusion, especially in low-income countries facing severe climate risk (FAO 2013).

Conclusion

Climate change poses a serious threat to agriculture, but 'Climate-Smart Agriculture' (CSA) offers a practical way forward. CSA can boost yields, protect farmers from climate-related shocks, and reduce emissions. However, its adoption depends on farmer education, land security, extension support, credit, and strong farmer groups. Policies need to be region-specific and farmer-centric. By combining modern technology with traditional knowledge and ensuring institutional collaboration, CSA can help achieve food security, climate resilience, and sustainable development for future generations.

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Review

Vital Crisis, Causes, Problems and Solutions for Sustainable Agriculture

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Abstract

Global agricultural systems face a deep-seated sustainability crisis due to the combined dynamics of environmental degradation, resource depletion, socio-economic instability, and institutional constraints. Growing demand to increase food production under climate variability, soil health decline, water shortage, and land-use competition has exacerbated vulnerability in both natural ecosystems and farming communities. This article systematically explores the root causes behind the crucial crisis in sustainable agriculture: yield stagnation, nitrogen dependency, land demand expansion, dietary transition, food loss and waste, inequitable distribution of food, and the eventual externalization of environmental costs. Special emphasis is put on emerging challenges in agrarian economies in developing countries, where farmer distress and production risks are compounded by climate change, market volatility, and policy inefficiency. Conceptual frameworks, along with empirical evidence, are used for assessing multi-dimensional management options: agroecological intensification, soil and nutrient stewardship, biodiversity-based land management, climate-resilient water usage, and food system transformation. The analysis underscores that transiting towards sustainable agriculture necessitates coordination in three main areas of intervention: production, consumption, and governance. Strengthening institutional support, aligning policies with ecological limits, and resource-efficient farming systems are all critical options for a long-term food security, environmental sustainability, and socio-economic resilience.

Keywords: Sustainable Agriculture, Climate Resilience, Agroecological Intensification, Food System Transformation and Resource-Efficient Farming.

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Introduction

The largest industry in the world is agriculture. It produces more than $1.3 trillion worth of food annually and employs over a billion people. Approximately half of the Earth's livable land is made up of pasture and cropland, which serve as both food and habitat for numerous species.

Critical habitats can be preserved and restored, watersheds can be protected and soil and water quality can be enhanced when agricultural operations are managed sustainably. However, unsustainable behaviors have detrimental effects on both the environment and people. Sustainable resource management is becoming more and more important. As the world's population increases, so does the need for agricultural products. One of the most crucial areas for conservation worldwide is agriculture because of its close relationships to human communities, the global economy and biodiversity.

What is the vital crisis, causes and problems for sustainable agriculture?

The shift from conventional to organic, greener or more sustainable agriculture is expected to provide a number of closely related major difficulties. Some of those crises were identified. Among all the possible challenges we highlight the following:

Maintaining yields: Following the 2007 and 2008 agricultural commodity price inflation, the idea of "food security" emerged as a pressing geopolitical concern once more. Two important ideas from the FAO Rome Summit on World Food Security were emphasized: in order to feed the world's nine billion inhabitants, food production must quadruple by 2050 and rise by 50% by 2030 (Maye and Kirwan, 2013). Despite the fact that this number was subsequently adjusted to 70%, there was a lot of uncertainty and assumption surrounding the estimations (Tomlinson, 2013). This problem is connected to many of the solutions that have been explored. For example, organic farming has a direct impact on soil health, biodiversity, and food safety.

Nitrogen requirements: The use of inorganic fertilizers is one of the primary barriers to organic agriculture, making it difficult to provide an appropriate supply of nitrogen (Muller *et al.,* 2017). In order to make up for this, legume rotations are frequently utilized for biological nitrogen fixation, which supplies nitrogen for the growth of non-legume crops either in situ or through imported manure. This suggests that there is less space available for the primary crops, which lowers organic agriculture's overall productivity in comparison to conventional agriculture.

Land demand: More land is required to produce the same quantity of yield if we believe that organic agriculture yields less (Muller *et al.,* 2017). Considering the legume rotations for N in order to achieve the same yield as with traditional agriculture, fixation requires 1.6 units of more area for every unit of conventional land (Connor, 2018). However, increasing arable land is not a practical way to lessen conventional agriculture's negative environmental effects. Changes in land use to increase agricultural land, such as turning wetlands, grasslands, or forests into arable land, result in the loss of ecosystem services (biodiversity, water control, sequestered carbon in soil and plants, etc.) as well as products (timber, fiber, energy, etc.). Considering the numerous environmental obstacles and problems (such as the growing competition for land from other human activities, the significance of the ecological functions of unfarmed land, expanding agricultural land is not viewed as an ecologically sound or practical solution due to the deterioration of large regions caused by unsustainable land management methods and the detrimental effects of agriculture on biodiversity (Bernard and Lux, 2017). More land could be set aside for organic agriculture for human consumption if the production and consumption of animal products were decreased along with the amount of food-competing feed from arable land. Therefore, a well-designed food system with more area devoted to organic agriculture, fewer animals and their food consumption, and less food waste must be addressed in order to feed the world's population in a sustainable manner by 2050 (Muller *et al.,* 2017). This challenge relates to efforts to reduce waste, produce food sustainably, and maintain land in a healthy natural state.

Dietary Changes: A method for more sustainable food systems based on the rational use of natural resources, decreased environmental consequences, and protection of human health is to lower the average demand for animal products worldwide and their proportion in human diets (Muller *et al.,* 2017). But dietary adjustments are insufficient to sustainable food systems. To maintain food systems within the limits of the planet, efforts must be made to reduce food waste and losses as well as adjustments to crop production and livestock (Westhoek *et al.,* 2021). A promising component of the solution for more sustainable agricultural output, food supply, and consumption is organic agriculture in conjunction with fewer animals used in livestock production and less food-competing feed requirements. Except for Cyprus, Finland, Ireland, Slovenia, Spain, and Iceland, the majority of European nations saw a significant decline in cattle between 1990 and 2019 (average of −28%) (Environmental Agency of Europe, 2021). According to model estimates, if relatively modest diets are adopted, organic agriculture could likely feed the world's 9.2 billion people by 2050 b Additionally, as eating and production are related, agriculture must be nutrition sensitive, not just concentrate on a small number of species, and address nutritional deficiencies in order to combat obesity and hunger. (Pretty and Bharucha, 2014). Because producing fruits and vegetables requires less land and more inputs, high-quality meals result in less farmland waste but more agricultural inputs in the form of water, fertilizer, and pesticides (Conrad *et al.,* 2018). This suggests that the association between high-quality meals and more effective use of agricultural inputs needs to be reversed. As previously mentioned, legumes can aid in this situation by supplying N to soils and guaranteeing a diet high in protein **(**Cusworth *et al.,* 2021). Action areas are connected to this challenge.

Food waste: There are several causes that relate to food waste in relation to the food industry like processing problems and also lack of appropriate planning. Food consumption patterns also play a key role for sustainable agriculture with regard to food wastage. According to (Conrad *et al.* 2018), the average US consumer produces a food waste equivalent to 30% of the calories available for consumption per day, a quarter of the daily food available for consumption, and 7% of annual cropland. Of the approximately one-third of the food produced globally that is not consumed, about 14% corresponds to postharvest loss. This is a practice mainly used in relatively rich countries to control market prices and prevent prices from falling below production costs. This practice has a high environmental impact because of the depletion of natural resources, which finally do not contribute to the market, often produced unsustainably using large amounts of water, nutrients, and agrochemicals. According to the United Nations Environment Programme, in 2021 a recent study estimated that 931 million of tonnes of food waste were produced in 2019 globally, of which 61% came from households, 26% from food services and 13% from retail.

Distribution and access to food: Apart from production, distribution and access to food are two key aspects to feed the world population. This to give people a broader understanding of solutions to prevent hunger, although it is not widely recognized, food is not included in the framing of food security, but this will be specific to the production side (Tomlinson, 2013). (Beckman *et al.* (2020) have forecasted that there will be people more compared to no adoption scenarios) following the adoption of agricultural input reductions proposed in the F2F strategy owing to higher commodity prices and reduced income reduction of trade), especially in Africa. However, this analysis only takes into account reductions in agricultural inputs, disregarding other measures to incentivize better food distribution and changing patterns of consumption that can lead to less food insecurity and more jobs and income. This issue is connected to the action areas.

Externalities: The threat of externalizing the damages caused by extensive agricultural practices to various countries is arguably the greatest threat associated with agricultural practices that are linked to the Green Deal, as cited by (Fuchs *et al.,* 2020). According to the authors, the EU member state is putting itself at a great threat of externalizing ecological damages to other countries, while taking the credit for green policies at home. For example, (Fuchs *et al.,* 2020) describes a situation where, unlike in the European Union, pesticide and herbicide use, and deforestation are more common in several countries outside the EU that supply oilseeds to the region. The EU recognizes the risk of externalities in the F2F strategy, in recognition of an appropriate accompanying EU food system that and the implementation of the necessary policies to enhance the raising of standards regarding the environment and social productions, which must be avoided.

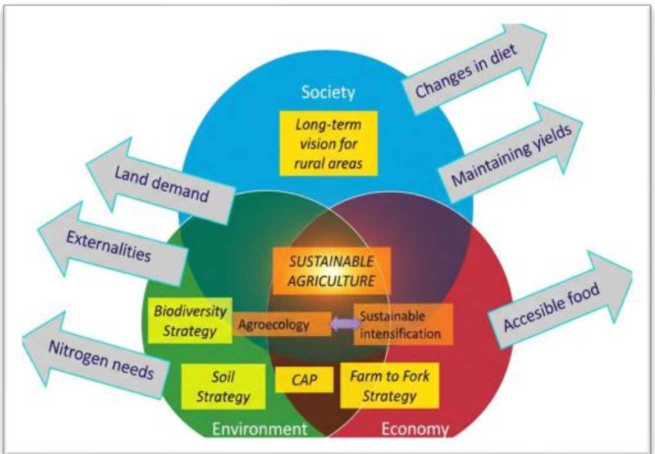

Fig 2. Conceptual framework illustrating the vital crisis in sustainable agriculture

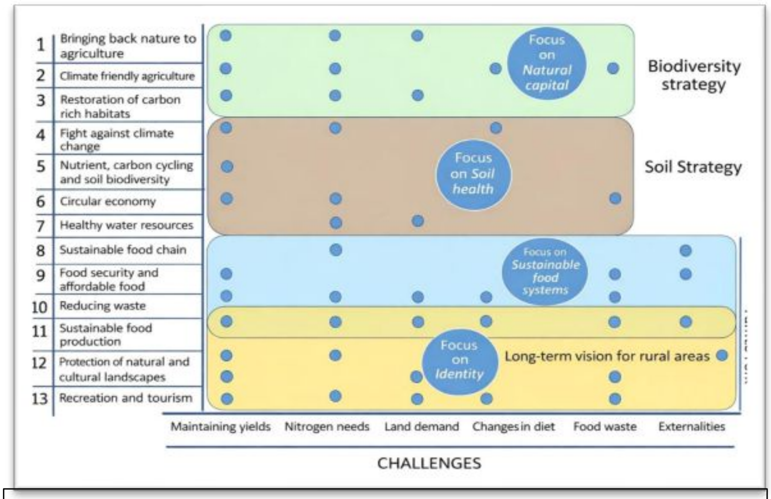

Fig 3. Overview of the relation between the main identified crisis and the 13 action areas of the four studied strategies.

Climate Change and Environmental Degradation: Climate change is a major problem confronting Indian agricultural activities presently. Harmering weather, increasing temperatures, and weather disturbances are causing havoc with the yield of crops and agricultural produce. An unsteady season for growth, pest infestations, and diseases are plaguing the minds of agricultural workers, devoted to the produce of this earth. Additionally, environmental degradation leads to the exacerbation of climate change, affecting agricultural activities adversely. Deforestation, or the clearing of forests, soil erosion, or the wearing away of soil, as well as the depletion, or the reduction in quantity, of natural resources, negatively influence the already vulnerable agricultural ecosystem negatively, owing to the improper unregulated use of fertilizers and pesticides.

Water scarcity and Irrigation Challenges: Water scarcity is the major problem Indian agriculture is facing today, coupled with deteriorating levels of groundwater and inefficient methods of irrigation. Due to the over-exploitation of underground water reserves without the appropriate infrastructure being developed for water management, large-scale water scarcity in farming areas has occurred. Most of the conventional irrigation techniques, like flood irrigation, are either not operational or very ineffective and inefficient. Due to this, equitable distribution of water is highly unequal, and the water-use efficiency remains abysmally low. The extensive area under coarse cereals cultivation further exacerbates the pressure on the already strained water resource base, aggravating the situation of water scarcity.

Market fluctuations and Price Volatility: There exist major challenges that Indian farmers face in the form of market fluctuations and price volatility, which have a direct bearing on the economic sustainability of the Indian farming sector. The volatility in the prices of commodities, coupled with the lack of adequate infrastructure in the markets and inefficient supply chains, makes the Indian farming sector more susceptible to challenges. In addition, the lack of transparent mechanisms in the determination of the prices of goods and the involvement of intermediaries in the markets pose greater challenges to the Indian farming sector. There exists the challenge of distortions in the market, as evidenced by the act of price manipulation and the act of hoarding the products of the Indian farming sector.

Policy Inadequacies and Institutional Reforms: The expansion and development of the Indian agricultural industry are restricted because of policy inadequacies and institutional barriers. The execution of effective crisis management techniques and agricultural innovation and modernization face challenges in consideration of outdated agricultural policies, bureaucratic inefficiencies, and fragmented government structures. Also, inadequate and insignificant changes in land reforms and accessibility of institutionalized credit facilities limit the potential of Indian farmers to effectively invest in modern agricultural technologies and adopt sustainable agriculture. The lack of changes and opposition to institutionalized reforms are responsible for sustaining the status quo and increasing the problems and challenges faced by Indian agriculture.

Management Strategies and Solutions for Sustainable Agriculture

Addressing the vital crisis in sustainable agriculture requires an integrated and multi-dimensional management approach that simultaneously considers societal needs, environmental protection and economic viability, as illustrated in the conceptual framework (Fig. 2). The solutions must focus on reducing negative externalities, improving resource-use efficiency and ensuring food security under changing climatic and socio-economic conditions.

Adoption of Agroecological Practices: Agroecology represents a key management strategy to overcome the environmental and productivity-related crisis in agriculture. Practices such as crop diversification, intercropping, crop rotation, use of legumes for biological nitrogen fixation, integrated pest management and organic amendments improve soil health, enhance biodiversity and reduce dependence on synthetic inputs. By strengthening natural ecosystem processes, agroecology helps maintain yields while minimizing environmental degradation.

Sustainable Intensification: Sustainable intensification aims to increase agricultural productivity on existing farmland while reducing environmental impacts. This strategy focuses on improving nutrient-use efficiency, precision farming, climate-resilient crop varieties and optimized water management. Sustainable intensification addresses the challenge of maintaining yields without expanding agricultural land, thereby preventing deforestation and loss of ecosystem services.

Soil Health and Nutrient Management Strategies: Improving soil health is central to sustainable agriculture. Soil management strategies include conservation tillage, organic matter recycling, balanced fertilization and site-specific nutrient management. Efficient nitrogen management through legume-based systems and integrated nutrient management reduces nitrogen losses, greenhouse gas emissions and water pollution, while maintaining soil fertility and crop productivity.

Biodiversity Conservation and Land Management: The Biodiversity Strategy plays a crucial role in managing the crisis caused by land demand and ecosystem degradation. Conserving semi-natural habitats, promoting agroforestry systems and protecting unfarmed land enhance ecosystem services such as pollination, pest regulation and carbon sequestration. Sustainable land-use planning prevents the conversion of forests, wetlands and grasslands into agricultural land.

Sustainable Food Systems and Dietary Shifts: Changes in diet and food consumption patterns are essential components of sustainable agriculture management. Reducing the consumption of animal-based products, promoting plant-based diets and increasing the use of legumes contribute to lower land, water and nitrogen requirements. Nutrition-sensitive agriculture ensures dietary diversity while reducing pressure on natural resources.

Reduction of Food Waste and Losses: Food waste reduction is a cost-effective solution to improve food availability without increasing production. Improving post-harvest storage, transportation, processing infrastructure and consumer awareness can significantly reduce food losses. Efficient food systems ensure better utilization of resources used in food production and reduce environmental externalities.

Improved Distribution, Access and Market Stability: Ensuring equitable food distribution and access is as important as increasing production. Strengthening supply chains, improving market infrastructure, reducing price volatility and minimizing the role of intermediaries enhance farmers' income security. Policies supporting fair trade, local food systems and rural livelihoods improve economic sustainability.

Climate-Resilient and Water-Smart Agriculture: Climate-smart agricultural practices such as drought-tolerant crop varieties, water-efficient irrigation methods (drip and sprinkler irrigation), rainwater harvesting and groundwater regulation help address climate change and water scarcity challenges. Efficient water management increases water-use efficiency and resilience to climatic variability.

Policy Support and Institutional Reforms: Effective implementation of sustainable agriculture requires strong policy frameworks and institutional support. Strategies such as the Farm to Fork Strategy, Soil Strategy, Biodiversity Strategy and Common Agricultural Policy provide incentives for environmentally friendly practices while supporting farmers economically. Institutional reforms, access to credit, extension services and technology adoption are critical for large-scale transition towards sustainability.

Fig.4 : Multi-dimensional management strategies addressing the vital crisis in sustainable agriculture

Conclusion

The vital crisis in sustainable agriculture encompasses the interrelationship between declining soil quality, inefficient nutrient and water utilization patterns, increased demand for arable land, changes in climatic patterns, and socio-economic factors. Concerns around nitrogen reliance, declining productivity in organic and conventional low-intensity systems, food losses, dietary pressure, and equitable food distribution add to the area of pressure on already stressed agricultural and natural resource systems. From the above discussion, it is made apparent that production-oriented strategies are not sufficient in achieving a more sustainable agriculture. Alternatively, integrated approach strategies encompassing agro-ecology, sustainable intensification techniques, soil and nutrient management practices, biodiversity conservation efforts, climatic and water-relate efficiencies in agriculture, and food system transformations are essential in producing a holistic and sustainable agriculture.

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