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# Green Pathways in Agricultural Science and Technology

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## ABSTRACT

*Agriculture is vital to global prosperity, sustainable development, and food security. However, climate change, socio-economic pressures, and regional environmental degradation—especially soil loss, erosion, and nutrient depletion—threaten the long-term viability of agricultural and food systems. While Governments and organizations worldwide have adopted sustainable food and agricultural policies, these frameworks do not sufficiently enable agronomic practices that promote water quality and preserve agricultural productivity. Green Pathways in Agricultural Science and Technology seeks to identify viable avenues to mitigate these adverse impacts through agronomic and technological transitions in agricultural systems across all crops, cropping systems, and regions.*

*The research questions guiding the work are as follows: What agronomic and technological practices, innovations, and systems increase productivity, resiliency, and sustainability while also maintaining or enhancing economic and societal viability? What boundaries and frameworks define these practices, innovations, or systems as "green pathways"? The manuscript comprises ten interlinked sections that clarify concepts, propose methods and innovations to increase sustainability, explore associated socio-economic and policy dimensions, present relevant case studies, and identify anticipated barriers and strategic research priorities. The concept of green pathways also provides a unifying frame for justification, evaluation, documentation, promotion, and diffusion of strategically selected practices that meet these criteria.*

***Keywords**: green technologies sustainability, Agricultural Science and Technology.*

## 1. Introduction

The introduction of Green Pathways in Agricultural Science and Technology presents the core thesis, objectives, and scope of the study, clarifying the relevance of research questions on sustainable pathways for agronomic science and technologies. The analysis places green pathways within the growing discourse on window-of-opportunity measures to mitigate environmental degradation and the emerging bioeconomy framework. Green pathways are distinguished from concurrent but different concepts such as green technology, sustainable agriculture, and innovation adoption. Tracing the evolution of sustainable growth perspectives and the increasing awareness of environmental pressures in agricultural development, the introduction frames the alignment of agronomic pathway approaches with the sustainable development goals.

In the face of environmental, economic, and social issues facing agriculture, the global shift towards sustainable development involves seeking economic development that does not compromise nature. Green pathways are measures, strategies, principles, practices, and technologies that aim to achieve agricultural productivity, economic growth, value addition, and farmer benefits while minimizing negative environmental impacts (Ag Info Project Design Team, 2007). Sustainable development forms the guiding theoretical framework for agronomic science and technology pathways, supporting clear definitions and delineation of incorporated options, dimensions, and practices (Deng et al., 2022).

# 2. Conceptual Foundations of Green Pathways

Sustainable agricultural intensification is characterised by what has been termed ‘green pathways’ guiding the development and implementation of innovations that conserve and enhance natural capital while simultaneously improving productivity, profitability, and other objectives. Green pathways in the agricultural domain are closely associated with agronomic practices and innovations aimed at achieving sustainable intensification and, particularly, the sustainable management of natural resources (e.g. soil, water, and nutrients). The term encompasses a wide range of agronomic practices, green technologies, biological innovations, and systems approaches. A more encompassing concept of the green pathway is therefore adopted.

More specifically, green pathways denote agronomic, additional, and broader green pathways that can contribute to achieving sustainable objectives while improving productivity, profitability, and other desirable outcomes. Green pathways, however, are complementary and supplementary to agricultural innovations that, by themselves, support productive and profitable advancement, but are not associated with natural resource conservation. Such innovations include essentially capital-intensive additions to machinery, equipment, and structure (e.g. advanced tractors and combine harvesters) and specific products (e.g. crop varieties that generally rely much on chemical inputs). Green pathways also signify the potential to improve the environmental aspects of agricultural initiatives without negatively affecting productivity and economic viability.

## 2.1. Definitions and Scope

Research on agricultural pathways often emphasizes the potential of inputs or practices to improve economic, environmental, or productivity outcomes separately. The concept of ‘green pathways’ accommodates all major agronomic, environmental, biological, energy, systems, digital, and social technologies, as well as innovative approaches at the crossroads of these categories. Historically, the biological dimension preceded energy, which preceded systems; biological, energy, and digital pathways co-evolved; and environmental techniques often predate contemporary approaches. This analysis adopts a technology-systems perspective, with the concept of 'green pathways' encompassing a rich variety of transformative initiatives globally, diverse yet interconnected owing to fundamental changes underway in the agri-food sector, with implications for sustainable agronomic science and practice. Green pathways embrace interconnected approaches across three clusters—biophysical, system-process, and socio-economic—that encompass a coherent spectrum of several dominant concepts widely referenced in the literature and employed by policymakers. Agronomic innovations targeting conventional practices often escape the green-academic terminology yet change cropping systems and practices substantially, augmenting agronomic research than the technological side they address.

A 'green pathway' is defined as a phased innovation involving technological, institutional, and socio-economic factors that transitions agricultural practices widely along a sustainable trajectory. Pathway systems differ considerably in their cores and features yet share an overarching focus on sustainability technology addressing problems associated with modern agriculture. Sustainable water-management strategy: across regions, crops, and time, developed feasible pathways and portfolios across agronomic, digital, socio-economic technologies constituting significant interventions in terms of water-management practices with the potential for widespread adoption. Residual-contaminant pathway: improve biomarker-toolbox detection and broader-characterization approaches to systematically identify, quantify, and understand factors governing the incidental occurrence of wide-ranging contaminants in agronomic systems and implement, monitor and evaluate concepts and tools that enhance nutrient, efficacy, and value while reducing the unintended persistence soil maintain or enhance productivity, quality, and profitability (KUMAR JHA, 2013).

## 2.2. Historical Development and Policy Context

The significance of agricultural science and technology as an important factor for the successful transformation of agricultural systems in Africa to meet the continent's challenges is currently highlighted by a series of international and continental initiatives. While widespread access to the broad adoption of agricultural science and technology will take time, many other much simpler agricultural improvement techniques and practices are readily available today and at little or no cost. These "green pathways" to agricultural improvement—explicitly defined within the confines of the research of agricultural science and technology—improve productivity while at the same time protecting the environment and enhancing food security and broad-based economic growth (Goulet, 2018).

The evolution of agricultural policy and practice has built a critically important foundation for today's current green agricultural science and technology pathways targeted at systematic agricultural production enhancement across Africa. By following a simple chronology of the policy timelines at global, country, sub-regional organizations (e.g. the African Union), regional (e.g. NEPAD), and local and urban policy-junction levels, a set of such policy-relevant drivers and barriers can be framed that impact the widespread adoption of the many readily available green agricultural technologies today. These policy-relevant drivers and barriers are routinely highlighted in the strategic policy-papers produced by the major ReSAKSS regional organisations in Africa.

# 3. Sustainable Agronomic Practices

Sustainable agronomic practices that help maintain agronomic sustainability of cropping systems are presented, focusing on conserving soil, water, and nutrients. Precise definitions of each of these principal components of sustainability are given. Emphasis is on practices and technologies that enable sustainable and precision agriculture to simultaneously meet society's needs for increased production and environmental protection. All agricultural enterprises depend on healthy soils free from erosion and salinity; efficient water management helps alleviate shortages of water for the increasingly competitive municipal and industrial users . Increasing concern over nitrogen leaching and run-off to lakes and streams, phosphorus run-off and sedimentation of lakes and reservoirs, and the debate over carbon sequestration in the soil have brought agricultural sustainability to the forefront . In addition, widespread interest in increasing energy efficiency, managing the risk of high energy prices, and alternative energy sources has stimulated further research on cropping-system sustainability (Pacceli Reis da Fonseca et al., 2019).

## 3.1. Soil Health and Conservation Tillage

Soil health and conservation tillage are vital for agronomic practices promoting sustainable production, resilience, and lower input dependency. Soil health, the capacity of soil to function as a vital living system supporting productivity and protecting human health, is assessed through biochemical and physical properties (William Jaster, 2010). Conservation tillage, any tillage system adopting practices that maintain at least 30% of the soil surface covered with crop residue after planting, reverses declines in soil health indicators due to conventional tillage, delivering global benefits at the same time. The system enhances organic matter, aggregate stability, and soil microbiota, improving soil structure, fertility and carbon sequestration; increases water retention and reduces erosion; boosts nutrient availability while decreasing input reliance; and lowers energy use and greenhouse-gas emissions (Basch, 2017). Six decades of experience confirm that, in semiarid conditions, conservation practices—minimum tillage, crop rotations, cover crops—positively influence soil health, while the long-term trajectories of soils under continuous cropping and conventional tillage are negative (Bhattacharya et al., 2020).

## 3.2. Water Management and Irrigation Technologies

Agricultural production is limited by soil and water resources, which are essential but under increasing pressure (Jensen, 1978). Access to water is becoming a critical factor for sustaining agricultural development and ensuring food security, especially in regions with scarce water supplies or poor-quality water. Water availability is being compromised by increasing demands from a growing population, urban growth associated with economic development, and changing priorities concerning water pollution and the environmental impacts of water use.

Scarcity of water resources is increasing not only in arid and semi-arid areas but also in humid regions where most water resources are already regulated to support irrigation (Schultz & De Wrachien, 2002). Against this background, improved water-use efficiency is needed to boost crop production and allow the same volume of water to be used for a larger crop area or for growing crops with a higher water demand. Water productivity, defined as the quantity of crop produced per volume of water applied, is receiving increasing attention as a means to improve water use and productivity at all levels. All of these factors highlight the need for careful planning, design, implementation, and management of irrigation and drainage systems at both regional and national levels.

Water management and irrigation technologies are essential for efficient water use in crop production. The application of water to a plant through irrigation must be done timely, accurately, and efficiently, especially in desert areas or locations where rainfall is not dependable. Surface irrigation is the most widespread irrigation method; emerging technologies in this field can provide high application efficiency with minimum labor and power requirements. In surface irrigation, remote sensing technology can be used to provide information regarding water application to individual fields for each irrigation, thereby permitting very precise amounts to be applied. If excessive amounts are applied, crop yield will decrease; water-logging will occur in many areas, especially during the rainy season; and soil salinity will be increased. Proper flushing and drainage facilities combined with crop selection according to the local situation are increasingly vital for success. Water management and irrigation technologies are therefore essential for efficient water use and crop production worldwide.

### 3.3. Nutrient Management and Fertigation

The nutrient management strategy focuses on planning and scheduling the use of fertilizer and organic amendments, and on managing soil health. Planning of nutrient application through precise scheduling is effectively achieved using fertigation, whereby fertilizer nutrients are applied through a water delivery system. Fertigation specifies the timing and amount of fertilizer applied in conjunction with water application. Nitrogen is a key nutrient supplied through fertigation, since it is mobile in soil and can be easily leached away from the root zone. Fertigation delivers nutrients uniformly and spatially to the root zone, where active plant roots area concentrated, and enhances water and fertilizer availability more evenly. Thus, fertigation improves resource use efficiency, enhances crop growth and land productivity, and maintains quality of produce. Such nutrient management practices can ensure proper input of fertilizer nutrients and reduce the risk of environmental pollution due to off-farm transport of fertilizer nutrients. Rhizobacteria play an important role in regulating crop-microbe interactions; the use of crop varieties inoculated with specific rhizobacteria strains can improve crop performance and are well known in the integrated nutrient management approach for large maize production areas (A Jat et al., 2011) (Kannan et al., 2015).

### 3.4. Integrated Pest and Disease Management

Integrated pest and disease management is important not only for the successful production of crops, livestock, and aquaculture, but also for securing a sustainable food supply for the growing global population. Integrated pest management (IPM) evolved in the 1970s, when the negative consequences of over-reliance on chemical pesticides became apparent, and it is widely recognised as a pillar of sustainable agriculture (A. ANDERSON et al., 2020). Resistance management is also critical: in a system that combines pest-resistant genetically engineered (GE) crops with conventional and other pest-protection practices, the long-term risk of pest resistance is diminished. Resistance management is another example of how the use of GE crops can complement agricultural practices already in widespread use and that are consistent with a sustainable approach to agriculture. The utility of pest resistance is especially significant in locations where the insect-transmitted dengue fever virus is common and where similar conditions support the emergence of this virus, which has serious consequences for public health and socio-economic development. Managing diseases and other microbiological pest problems in an agricultural system based on pest-resistant GE crops is a challenge. The increasing importance of wine and table grapes as export commodities in many developing countries is expected to spur continued expansion of infected areas for this pathogen. Agricultural systems that emphasise the use of multiple complementary agroecological practices—such as reliance on crop diversity, cover crops, reduced tillage, organic amendments, polycultures, and diversification of pest control tactics—can reduce reliance on both synthetic inputs and GE crops while being consistent with the broader objective of sustainable agricultural development.

## 4. Green Technologies and Innovation

Investments in green technologies will increase agricultural production while protecting environmental quality. Green technologies have been classified into digital, energy, biological, and systemic innovations (Yao & Wu, 2022). Digital technologies apply computational power to manage farming operations and resources. Energy innovations reduce fossil fuel dependency by integrating renewable energy and storing power on-site. Biological research focuses on crop resilience, pest resistance, resource-use efficiency, nutritional quality, and food-waste valorization. Systemic approaches evaluate how component interactions can optimize farming practices, hence conserving water, fossil fuels, pesticides, agrochemicals, and nutrients (Aithal & Aithal, 2016).

### 4.1. Precision Agriculture and Sensing Technologies

Precision agriculture offers resources and technical support for efficient farming (Hudzari Razali et al., 2013). Observing a growing interest in soil health and continuous improvement, South African farmers use agricultural technologies to collect and monitor data. Digital agricultural innovations, from drones and satellite images to soil monitoring and fertiliser spreaders, introduce new modelling, precision farming, and data-capturing techniques. Large amounts of diverse and unstructured data present a challenge for agricultural models (Kim & Hwan Lee, 2022). The datasets used in agricultural scientific models covered soil, weather, crop growth, remote-sensing, and farming practices. Precision agriculture collects and analyses these datasets to support decision-making. Active research develops sensors for collecting relevant variables, such as moisture sensors and multispectral cameras (Arnó Satorra et al., 2017).

## 4.2. Renewable Energy Integration on Farms

Green agriculture provides a production framework, whereas green pathways enlighten agronomic practices, farm management, and policy instruments. Presently, green pathways focus on digital, energy, biological, and systemic innovations. Accurate climate-smart designs provide farmers with essential sustainable considerations.

Farms encompass diverse energy requirements during production. Energy remains a pivotal on-farm topic that heavily influences agricultural sustainability, likewise, farmers have been transitioning toward renewable energy sources. Agricultural mechanization and greenhouse production make greenhouse gas (GHG) emissions unavoidable. Livestock loses exacerbate this dilemma, with worldwide GHG emissions surpassing..........tonnes. Nonetheless, farm energy costs escalate annually, fixed input and product prices fluctuate, and energy demand soars according to economic growth, waste treatment, urban expansion, and lifestyle changes. To offset energy and production cost increases, renewable energy generation becomes curial. Inexhaustible energy resources embarrass the entire system, volatile energy input prices—especially fossil fuel—complicate management, and large energy-carbon dividends remain unexploited. Sustainability aids agricultural development. Renewable energy significantly alleviates energy-carbon debt. To minimize production expenses while fulfilling green pathways or carbon-neutral policies, energy configuration alone is insufficient, and biophysicals belief investments (the nature of energy) demand serious contemplation and situational adaptations.

On-farm renewable energy supply estimates (Kossey, 2011). Accurate determination of total on-farm energy supply indicates the system in hand. Lifecycle ary configurations (Cristina Vlad & Liliana Berevoianu, 2014) of renewable energy stand severally standard and well-distributed over a farm, rely only on a few crucial operation permits and make value-chain evaluations simply traceable. Although capital expenditure might substantially differ across agronomic sectors, the field efficiency of fixture energy component holds often denotes the system. Confusions arise from tank type, cellar requisites, and corresponding energy-saving options. Water chemistry, salinity, and acidity variations among region and land exert sizeable cost indulgence. Higher technologies easily appear redundant due in not maintaining the threshold status of the overall system but actually rather predictive, observational datasets and function restoration of imminent configuration sustain onset inspirations.

Meanwhile, due-horse approaches settle on larger-scale installations which rise the return on capital aspect but at the dead-end of infrastructural path. In contrary thus, it signifies evenwider and shallower valuation of fixed outputs instead of background plurality or fluctuating situation and building effort originally. Water casts scrutiny upon mixture and thus when alone crop extends steady operation and heterogenous crops proceed thereafter at larger field scopes as compatible or paralogous differential unless crop sets filters stricter, enabling absent-intlay passed yet reevaluated.

Society disallow stipulate dependence on consumptions and capital proposals; experimental installations still await devising onward. Prior theoretic decorum focuses on speculative interconnections or solely energy side on general tier supply install but seem way away from misunderstand design-storage necessities meanwhile equipment guidance stipulating notTide-forwind-oriented or isotope-incentive-inclusive. Reproductive output longer term men need firm regularity-cum-firmled nor hinges on neighbouring grounds-in-simultaneously-yet- excludes-shrink. Absorb anticipation-only remains valid, elevado. Universally thus indicating series followed. Tracing diagrams-to-waste-converting apert undergone typenour-laden, foreground away-larger achterkant, however even apsidally tended site. Ex-appearance cut through fulcrum-in-place-originated species-observable. Installation-side clientele remedied nevertheless guiding likewise preinstallation-exempt subsided—this-not-that-validated-reaching still inventory sufficed.

## 4.3. Biotechnologies and Genetic Improvement for Sustainability

Technologies ultimately aim to deliver solutions under tight climate constraints. Biotechnologies and genetic improvement represent the intersection between extreme adaptations and restoration of more sustainable productivity conditions in the harshest environments, at least on certain agricultural systems. Various gene-editing, marker-assisted technologies, and RNA interference (RNAi) applications exploit adapted varieties and restore productivity under heat, salinity, drought, and waterlogging.

Global warming impacts higher temperature adaptations. High temperature, drought, and salinity have historically been stable mutations adapted to such systems. Selected genes related to salt, drought, and heat across important crops are characterised. Leads that provide increased tolerance of either heat or drought are identified. In other crops, stability is shown under asymmetric flow, and an important drought tolerance gene is transferred. “Heat shock factor”, “dehydrin, and “GolS”, selected for the drought tolerant variety FD-3, are present in salt-tolerant varieties. Stress-combinations able to twin are worked at the genomic level. Selected genomes exhibit simultaneous significant improvement in high temperature and drought (E. Hoffman, 2022).

## 4.4. Circular Economy Approaches in Agricultural Systems

The circular economy approach is essential for sustainable development of agricultural systems (G. Santeramo, 2022). It moves from a linear pathway of resource use and waste toward closed and regenerative loops. Waste valorization through resource recovery prevents contamination of soil and water while regenerating nutrients, organic matter, and energy in agricultural systems after utilization (Yang et al., 2022). Circular economy practices beyond the farm can extend agronomic sustainability, as sustainably produced biomass, byproducts, or residues supply inputs for food or bioeconomy. Traditionally considered at a supply chain level, a circular economy at the scale of the farm instead creates closed nutrient loops responsible for managing urban waste resources. Strategies within farms replenish depleted nutrients caused by cropping or livestock systems that exhaust soil, biomass, and society resources. Circular approaches valorizing waste for humic compounds and biostimulants or integrating high-value bioprocesses to extract nutrients, energy, or biobased valorizing products facilitating nutrient recovery thus enhance sustainability while supporting further renewability practices.

# 5. Agroecology and Ecosystem Services

Agricultural ecosystems, serving as the foundation of food systems that sustain life, require special consideration regarding biodiversity loss. Biodiversity is recognized as the cornerstone for developing sustainable agricultural systems worldwide. It has a crucial role in enhancing the resilience of agroecosystems to withstand climate change (Palomo-Campesino et al., 2018). A pollinator-friendly design influences service delivery in perennial crop systems, while habitat restoration contributes to the resilience of agricultural landscapes in both smallholder and large-scale farming contexts. Ecology-driven diversification of agroecosystems can implement better system-level designs (Gascuel-Odoux et al., 2022). The agroecological design of crop production systems aiming to structure ecological interactions and leverage synergies between crops and livestock helps gradually transform conventional monoculture into more resilient, multifunctional systems capable of adapting to climatic hazards when associated with climate-smart agricultural practices and transformative knowledge.

## 5.1. Biodiversity-friendly Farming

Biodiversity-friendly farming fosters natural capital through practices that increase below-ground biodiversity, retain or increase above-ground biodiversity, and reinforce ecosystem interactions to enhance resilience. Agricultural infrastructure can also provide habitat for nature's reservoirs of biodiversity. Structural measures include restoration of hedges, windbreaks, ponds, and flower strips buffering fields, which are crucial to stimulating species recovery.

Cover crops enhance biodiversity, notably by establishing vegetative cover between main-crop cycles. Their plant diversity promotes above-ground biodiversity, while species with an active root system encourage below-ground biodiversity, fostering a healthier and more resilient ecosystem. Intercropping enhances above- and below-ground biodiversity and can be combined with cover cropping. The historical Trojan horse effect of crop-breeding restricting intercropping to legacy systems has perpetuated ecological degradation.

Diversifying the cropping system, such as increased species mosaic, and integrating livestock provide opportunities for further biodiversity-friendly practices (Stringer et al., 2019). Connecting neighbouring farms contributes to establishing ecological corridors; high nature-value farming revives abandoned agricultural land to biodiversity-friendly production; and farmland conservation and restoration in peri-urban landscapes improve nested biodiversity protection. Roma, high-nature-value farms can be branded as a marketing instrument, enriching agricultural activity and producing harmless animal-derived inputs for recreation and wreath decoration in urban settings.

### 5.2. Pollination, Habitat Management, and Resilience

Across the globe, the intensification of food production continues to threaten the sustainability of agricultural systems. Significant biodiversity loss has been tied to this trend, particularly through the decline of pollinators. Pollinator-dependent crops are vital for food quality, diversity, and nutrition, yet their production is threatened by pollinator decline. The adoption of ecological intensification practices is expected to help secure pollination services. Pollinator habitat management practices increase the availability of floral and nesting resources. Thus, improved understanding of the relationships between pollinators, their environment, and the ecosystem services they provide is required. Significant gains in knowledge have enabled enhanced configuration of agri-ecosystems that support biodiversity and ecosystem services (Kovács-Hostyánszki et al., 2017).

### 5.3. Climate-smart Agroecosystems

Climate-smart agricultural practices encompass those that increase productivity, make farming systems more resilient to climatic shocks, and/or reduce greenhouse gas emissions; the three attributes are interrelated rather than mutually exclusive. By contrast, a climate-smart agroecosystem is designed to deliver multiple climate-related benefits—rehabilitating degraded areas, improving food security and nutrition, recovering carbon captured in the soil, reducing pests and diseases, and reducing dependency on synthetic fertilizers. Building climate-smart agroecosystems, a priority in many countries, requires an adapted set of measures (Hellin & Fisher, 2019).

Strategies for climate-smart agroecosystems include identifying local agroecological conditions determining the types of climate-smart practices practicable and species and varietal choices, deploying participatory approaches to ascertain farmers' needs and priorities, keeping pathways upscale, working with the enabling environment to address policy demands, promoting collective action to increase farm viability, building on piloted options to clarify second-order effects, and establishing cross-sectoral teams and coalition of coalitions to broaden concepts (M Mandapati, 2018).

## 6. Socioeconomic and Policy Dimensions

Sustainable agriculture is fundamental for ensuring food security, mitigating climate change, and conserving natural resources (G Ryan & C Spencer, 2001). In addressing sustainable agriculture, technologies, agronomic practices, circular economies, agroecologies, ecosystem services, and environmental impact assessments are relevant (G. Ballantyne et al., 2010). Literature documents the adoption of sustainable agriculture (Green Pathway) following a sequence that literature has not previously addressed.

Pathway adoption is feasible and has been prescribed in several policy documents. Its successful implementation is achieved through the establishment of collaborative networks among scientists, farmers, and agricultural industry stakeholders. Various organizations, such as universities, faculties, or cooperative extensions, government departments responsible for agriculture and natural resources, non-governmental organizations (NGOs), and private companies have fostered collaborative networks that facilitate the transfer of scientific knowledge to enhance agricultural sustainability.

Understanding the viability, enabling conditions, and socio-economic policy instruments associated with these pathways is vital for agricultural sustainability and for the formulation of appropriate policies, legislation, and regulations regarding sustainable agronomy and related subjects, particularly in developing economies.

## 6.1. Economic Viability and Risk Management

Conventional chemical technologies predominate in agriculture throughout the world. Newly introduced green technologies often emphasize environmentally friendly processes but are not necessarily widely adopted. Farmers sometimes regard these innovations as secondary to conventional approaches. Consequently, economic viability, investment return, regulation, and price-support policies have a crucial influence on the introduction and implementation of innovative technologies (Welch et al., 2009).

Although many methodologies that can potentially improve agricultural sustainability are available, few offer a better economic profile than those being applied today. Under conventional technologies, farmers attempt to maximize productivity, while many green or innovative technologies promise moderate improvements in productivity with a lower environmental footprint. Such trade-offs pose challenges for sustainable development. These challenges can best be addressed through agri-food mandates, value-chain arrangements, and business models that assure the commercial viability of continuous investments in agri-food technologies (Ag Info Project Design Team, 2007).

## 6.2. Policy Instruments and Regulation

Policy instruments, both economic and regulatory, influence the implementation of green pathways. Instruments and regulations can encourage and support sustainability practices either directly by providing incentives or indirectly by prohibiting unsustainable practices. Although policies are adopted at various scales, national policies tend to create the largest shifts in market conditions and incentivise private-sector investment (Ganda, 2023). Green Policy 2030 of the Republic of Korea is aligned with the UN Sustainable Development Goals (SDGs) and the Paris Agreement, and targets a conversion of 30 per cent of agricultural land to organic farming by 2030. Adoption of green production technologies is generally observed to be greater in countries with policies such as the US Federal Agricultural Improvements and Reform Act, the Ukraine Agricultural Sector Development Strategy, China's Agricultural Supply-side Structural Reform and the EU Common Agricultural Policy (Liu & Liu, 2023).

### 6.3. Education, Training, and Knowledge Transfer

Agricultural education, training, and knowledge transfer are vital for building and keeping the country's human capital, increasing capacities among farmers and other stakeholders, and helping agricultural policies and programmes achieve their objectives. Education, training, and knowledge transfer are crucial for increasing knowledge and understanding among agricultural policy planners and administrators, highly relevant at both the national and local government levels. Knowledge transfer facilitates the dissemination of both conventional and cutting-edge practices that comprise green pathways: such practices adopt selective approaches to the use of various inputs and are supportive of emerging technologies. The serious shortage of human resource capacity in the agricultural and rural sector in the Philippines is a key constraint to achievement of the Philippine Medium-Term Development Plan.

## 7. Case Studies in Green Pathways

Agriculture is facing tremendous challenges globally, including global population growth, food insecurity, climate change mitigation, and environmental degradation. Increasing pressure on farmland is accelerating the transition towards sustainable agricultural practices in order to improve productivity, achieve climate-smart agriculture, and promote the sustainable use of farmland through the liaison of policies, technology, and knowledge transfer. Green Pathways, therefore, aim to enhance research and innovation policies that address agriculture-related challenges while considering socioeconomic and environmental sustainability.

Two recently established networks on precisely targeted and sustainable agriculture illustrate concrete applications of Green Pathways concepts. The first, the International Network for Research and Development on Precision Agriculture, formally launched in October 2020, spans the Asia-Pacific region. The principles of precision agriculture reflect the increasing necessity of policies adapted to context-specific situations. The second network focuses on sustainable agricultural practices and was formally established in January 2021. It aims to enhance the sustainability of agricultural farming systems by promoting appropriate technologies and methodologies adapted to the agricultural, environmental, and socioeconomic constraints of each region.

These two networks illustrate the critical importance of place-based, context-specific, and stakeholder-oriented research, development, and innovation strategies. Separation occurs both at regional and worldwide levels, with significant impacts on agricultural productivity and food security, especially in countries with smaller farms or limited capacity to adopt Green Pathways (G. GABOY et al., 2019).

### 7.1. Case Study Networks in Precision and Sustainable Agriculture

The increasing urgency of addressing global challenges, including climate change, food insecurity, and ecosystem degradation, highlights the need for innovations in agricultural science and technology (AST). To facilitate the transition towards sustainable agricultural systems, the AST community is embracing the concept of green pathways, which encompass a variety of innovative methods that foster unique agronomic and ecological configurations for sustainable agriculture. Green pathways align with the core principles of the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change.

Green pathways in AST can be defined as the ongoing development and dissemination of technologies, innovations, and measures that progressively align agricultural practices with the principles of sustainable development and reduced environmental impact. In practice, a multitude of distinct pathways currently exists, including energy-efficient tractors, precision irrigation devices, biopesticides, robots, remote sensors, data loggers, soil enhancement ingredients, and shade covers. Agricultural output has been a subject of extensive academic and technical investigation, with many studies exploring approaches aimed at sustaining food production while simultaneously protecting the environment (Meijer et al., 2011). These analyses have consistently indicated that, in addition to technological advancements, the integration of policies, legislation, education, sociocultural dimensions, and marketing strategies remains paramount in the quest for sustainable agriculture.

The concept of green pathways permeates all aspects of sustainable development, including environmental, economic, and sociocultural considerations, and pertains to the cropping and agricultural community at large. Numerous institutions, agencies, and organizations are committed to fostering green pathways and promoting their dissemination. An analysis of existing networks and organizations dedicated to advancing green pathways in agricultural science and technology (AST) reveals a range of case study activities and implementers that warrant closer examination (Javier Ferrández-Pastor et al., 2016).

## 7.2. Regional Implementations and Outcomes

Regional implementations vary considerably among the twelve networks. The Polish network, for example, has successfully developed an assessment tool for agronomic practices, using readily available data to summarise regional and national indicators related to performance, productivity, and sustainability, enabling policy and research prioritisation (Ag Info Project Design Team, 2007). In West Africa, meanwhile, the performance of integrated soil fertility management is evaluated through partnership with an international research centre and the involvement of various stakeholders. Macroeconomic and productivity studies in North Africa focus on crop-water productivity and the economic benefits of irrigation. Other networks explore a variety of practices, technologies, and innovations, implementing continental indicators for agronomic performance to track locally relevant determinants of sustainable intensification.

Implementation experiences yield several lessons. In the West African regional network, the instigation of a new multi-stakeholder forum helped mobilise further collaboration in agronomic sustainability enhancement. The North African network has been able to stimulate national deliberation on various indicators of agronomic sustainability by linking biophysical and economic 3e268f34-849a-4d45-bce2-e2e5b73be5ebrmation. In the Polish region, interaction with policy actors concern-for sustainability issues and propositions initially regarded as unfeasible.

## 8. Evaluation Methods for Green Pathways

Green Pathways, outlined by a multitude of definitions, aim for a more sustainable agronomic future by shifting operational paradigms and harnessing innovations. Within the scholarly literature, numerous evaluation metrics and systematic tools have been developed to elucidate such pathways and gauge their progress. These include a spectrum of sustainability indicators (Scharfy et al., 2017) , indices grounded in established cultivation criteria, and various life cycle assessment approaches (Deng et al., 2022). Covered frequently within these frameworks are conventional and precision approaches, alongside chemical- and non-chemical methods.

From the groundwork established via phase 1, a set of metrics has emerged to typify greener operations in precision and sustainable agriculture. On a regional scale, procurement of energy data from watercourses, central pivot systems, and embedded monitoring equipment gives access to comprehensive reports. Adopting a similar ethos, exploration into methods employed by the Agri Benchmark network has unlocked additional avenues for analysis. To transition towards widespread adoption, mechanisms for self-governed monitoring, rigorous evaluation, and continuous enhancement akin to established feedback loops remain to be disseminated, catalyzing progress in guidance and collaboration.

### 8.1. Metrics, Indices, and Life Cycle Assessment

Environmental sustainability assessments of agri-food systems can be performed using indicators, life cycle assessment (LCA), and multi-criteria analysis (MCA). Indicator-based assessments are simple, quantitative tools used to communicate overall trends in the economic, social and environmental development of a region or system (Gava et al., 2018). LCA identifies product-related flows associated with the production and consumption of commodities across spatial scales from local to global, thereby supporting decisions regarding necessary changes to materials, processes, and management (<1977> Fantin, 2019). MCA considers environmental, economic, and social impacts of agricultural systems while integrating stakeholder perceptions and preferences to identify trade-offs. In transitions to agri-food systems aligned with the sustainable development goals (SDGs), evaluation of economic and social aspects alongside bio-physical metrics remains critical.

LCA quantifies environmental impacts and/or toxicity potentials of substances, mixtures, and products across any type of technical system, which makes it suitable for evaluating inputs and outputs of agricultural production systems. ISO 14040 and ISO 14044 establish general principles, framework, and requirements, and comprehensive LCA of Costa Rican pineapples, the dairy sector, pesticide environmental profiles, and biofuels has been conducted in accordance with these requirements. Mathematical models originating from pesticide and pollutant fate-analysis permit the systematic assessment of the dependence of degradation processes on soil conditions. Consequently, for atrazine, it has been established that degradation half-lives in dry, neutral, and acidic conditions are very sensitive to soil pH and generally increase with soil organic carbon (OC) content. A model for surface-runoff-estimated deposition allows quantification of ecotoxicity impacts of pesticide applications in biofuel crops and of systemic, contact, and preventive stimulations in strawberry production and greenhouse vegetables. Environmentally extended multi-regional input-output LCA has been extended for the comparative assessment of carbon-water footprints of different agri-food products and systems. Models permitting the quantification of both carbon footprints and water footprints have been developed and implemented for Costa Rica at the national scale and in various other countries and regions. An approach enhancing the understanding of the role of cultivated ecosystems in mitigating, amplifying, or having no significant effect on gases emissions is the incorporation of ecosystem services into greenhouse-gas assessments.

### 8.2. Monitoring, Evaluation, and Continuous Improvement

Monitoring evaluation and continuous improvement involve the identification of good or better practices based on the degree to which associated outcomes align with stakeholder objectives. In agricultural landscapes, for example, aims include enhancing production of crops, livestock, and fisheries, improving worker conditions, bolstering water, soil, and air quality, contributing to climate-change mitigation, and delivering associated social and economic benefits. When new information, interventions, or regulations arise, it may become necessary to revisit assessments to refresh overall goals, narrow or extend the scope, alter indicators, or adjust specific targets. The proposed assessment framework applies to contrasting case study areas characterized by large-scale, high-input commercial agriculture in Mexico and by small-scale, low-input family farming in Guatemala. Significant differences exist in adopted practices, vulnerability to climate-change impacts, and social, economic, and environmental conditions. Although these assessments remain ongoing, the process itself serves to build capacity within local communities, reinforcing the value of an iterative approach to continual improvement, indicator development, and stakeholder engagement.

## 9. Barriers, Enablers, and Ethical Considerations

Agricultural practice is influenced by technological innovation, sociocultural dynamics, regulatory frameworks, and (as demonstrated by the current COVID-19 pandemic) new and unforeseen events. Historical evidence indicates that innovations involving biopesticides, biotechnology, conservation tillage, and integrated crop management can support both economic viability and environmental performance (Matus et al., 2017). Precautionary measures must be taken to determine and respond to associated social, economic, and ethical issues. Addressing social dimensions—including decision-making roles, cultural attitudes, and individual motivations—can enhance implementation legitimacy (Christian Rose & Chilvers, 2018). Equity and access responses are similarly necessary, both to ensure fair distribution of technologies and to deliberate on decisions about design, development, and dissemination.

Green Pathways in Agricultural Science and Technology outlines the scientific, technological, and policy innovations required to realize a green agricultural pathway capable of supporting a sustainable global agri-food system under climate change. Analysis of the practices and technologies along the pathway reveal social, cultural, equity, and access dimensions that influence adoption and legitimacy. While frameworks for assessing policy-relevant drivers, barriers, and strategic opportunities can effectively guide green pathway assessments, ongoing proactive efforts are vital to integrate these principles into agricultural practice and ensure timely delivery of co-benefits across policy objectives and sustainability dimensions.

### 9.1. Social and Cultural Dimensions

Social and cultural dimensions influence adoption and legitimacy. Constraints exerted by socio-cultural factors appear particularly salient in low-income countries for both farmers and researchers; farmer adoption may be influenced by peers, community leaders, and extension service agents involved in agricultural decisions (G. Ballantyne et al., 2010). In rich countries, some classical and systemic innovations may be resisted if they contradict established farmer practices, knowledge, and local culture. Communities might reject change that, while technologically beneficial, somehow compromises deeply ingrained traditions, a universal instinctively rooted phenomenon. Longitudinal observations of farmer attitudes towards agricultural technology show considerable variability over time, suggesting that agri-food system socio-political influences are both dominant and temporally dynamic (Christian Rose & Chilvers, 2018).

### 9.2. Equity and Access to Technology

Although science and technology transform agriculture, inequity and access can threaten their full adoption, endorsing wider participation and addressing urgent agricultural challenges. The challenges of food safety, security, and sustainability increase amid a rapidly growing population, limiting natural resources. Subsequently, the demand for agricultural innovations skyrockets. Tackling this bottleneck depends on access to scientific knowledge, technology, and funding by equipping governments, advisory networks, businesses, organizations, and farmers with the critical mass of information needed to address local agricultural needs (G. Ballantyne et al., 2010). Technology can deliver agricultural knowledge address urgent challenges.

## 10. Future Outlook and Strategic Research Priorities

Future research priorities aim to foster sustainable agricultural intensification amid challenges like climate change, land degradation, declining biodiversity, and population growth. Key unmet needs involve increasing resource-use efficiencies; designing field-planted, resilient, resource-efficient, and multifunctional systems; delineating sustainable-intensification evaluations; and enhancing stakeholder engagement. Institutional frameworks, cultivation standards, and assessment systems must also be improved to facilitate progress towards the United Nations Sustainable Development Goals. Barriers and incentives to adopting green technologies must be addressed at all levels, and collaborations and funding must be encouraged across public-private, interdisciplinary, and national-international dimensions. Comprehensive strategies should integrate technological, systemic, and agroecological innovations to achieve transformational changes in agronomic practice and ultimately reshape agricultural research priorities (Henkhaus et al., 2020).

# 11. Conclusion

Green Pathways describes sustainable practices, technologies, and policy dimensions that can mitigate the agricultural sector's detrimental impacts on land, air, and water. To sustainably improve food production and security while responding to climate change and other, progress must address these challenges. Motivation and action are strong, as exemplified by the dynamic agronomic sustainability and green technologies agendas that have emerged worldwide over the last two decades.

The four types of pathways—agronomic, green technologies, agroecology, and socioeconomics—are not mutually exclusive or comprehensive. Many practices, technologies, and policies of interest belong to more than one category or to none at all. Reducing the consideration of these items to a single category was impossible without impractical vagueness. Pathways are not merely synthetic; they also illustrate nested agenda formation. Agronomic sustainability is usually a precondition or foundational item, from which green technologies and agroecology can be added. Socioeconomic dimensions, while frequently advanced as the key to broadening the sustainability agenda, often join last.

Formulating the triple system sustainably is vital. Compromise in accommodating food security, climate-change mitigation objectives, and other major drivers diminishes agricultural development quality, capacity, and momentum. More sustainable technologies, practices, or policies not only promote food security and mitigate climate change, but also reduce other detrimental environmental effects. (Ag Info Project Design Team, 2007)

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