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Agricultural innovations for sustainable environment and profitable farming

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ABSTRACT

There has been much research on innovations that have emerged in global agricultural systems, including greenhouse farming, hydroponics, precision agriculture, and organic farming. However, much of the research to date has focused on measuring these technologies separately or using very limited performance metrics (e.g., yield). This lack of context, combined with the lack of information regarding the degree to which different technologies may be adopted, creates challenges related to understanding the economic feasibility of different agricultural innovations as well as evaluating their role in sustainable transitions.

Purpose: This study systematically reviews and critically examines major agricultural innovation pathways and their role in enabling sustainability transitions. Using Socio-Technical Transition Theory (STT) and Innovation Diffusion Theory (IDT), it evaluates the environmental and economic sustainability of agricultural innovations reported in peer-reviewed literature published between 2003 and 2025.

Method: A PRISMA-aligned, qualitative literature review was conducted using a variety of databases like Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar to identify published studies focused on agricultural innovation initiatives for which the author had access to full-text articles. Thematic synthesis of the collected data was used to interpret: 1) innovation performance, 2) institutional alignment with innovation, and 3) adoption pattern of the above innovations.

Findings/Results: No single agricultural innovation emerged as universally superior in terms of sustainability performance. While greenhouse farming and hydroponics achieve high productivity and resource efficiency, they require considerable investments to attain economic viability. Precision agriculture improves input management and reduces production risks but demonstrates greater effectiveness in large-scale farming systems than in smallholder settings, highlighting the context-specific nature of agricultural sustainability transitions.

Substantial heterogeneity ($I^2 > 90\%$) highlighted environmental and management influences but did not negate consistent positive breed performance. Overall, the evidence confirms that the Kalahari Red goat integrates productivity and resilience, supporting its strategic role in climate-smart genetic improvement programs.

KEY WORDS

Sustainable agriculture; Agricultural innovation; Profitability; Socio-technical transition; Agri-innovation diffusion

ARTICLE HISTORY

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Introduction

Globally, agricultural systems are under increasing pressure to enhance productivity while simultaneously reducing environmental impacts and maintaining economic viability. Climate variability, declining soil fertility, water scarcity, rising input costs, and biodiversity loss have exposed the structural limitations of conventional input-intensive farming systems [1,2]. Consequently, there is growing demand for agricultural production systems that can simultaneously improve producer livelihoods and ensure the long-term sustainability of natural resources [3]. Modern agriculture is being revolutionized by the demand to reconcile ecosystem management and financial sustainability. Innovations in agriculture including precision technologies and constructions of climate resilient concepts are integrating hybrid social business models in rural economies [4]. So, if we see through the lens of new innovations, seeks to broaden the paths toward economic cultivation while safeguarding the earth for coming generations. Table 1 shows the macroeconomics and development indicators through innovative agricultural practices.

Table 1. Macroeconomic and development indicators of agricultural innovations.

Metric	Baseline Data/Statistics	Role in Economic Development & Profitability
Global GDP Value Unlocked	$500 billion in added value projected by 2030	Driven entirely by advanced IoT connectivity, automated machinery routing, and real-time data analytics.
Share of Global GVA	Fluctuates between 4.01% and 4.38% globally (approx. $4.03 trillion)	Establishes the foundational raw-material base for multi-trillion-dollar downstream industries like food processing.
National GDP Share (Emerging Markets)	Accounts for 16.38% to 18.00% of total domestic GDP in major agricultural nations	Stabilizes national macro-growth cycles by anchoring domestic consumer demand and ensuring food supply security.

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Net Farm Yield & Per-Capita Income	Localized crop yield increases ranging from 30% to 200%	Substantially outpaces the initial overhead of tech adoption, translating into a net gain in per-capita income.
Sector Growth Acceleration	Agricultural GVA expanding at a resilient 3.1% to 3.6% annual growth rate	Acts as a critical buffer during economic shocks; allied sectors like livestock grow faster, diversifying income.
Poverty Reduction Index	Extreme rural poverty dropped to 5.3% globally under revised $3/day metrics	Heavily supported by tech-driven rural initiatives, drone resource mapping, and localized digital crop advisory.

Note: Data compiled from multi-institutional economic evaluations across the 2025–2026 fiscal periods.

GVA = Gross Value Added; GDP = Gross Domestic Product; IoT = Internet of Things.

Sources: [5-11].

Several agricultural innovations have emerged as potential responses to these challenges, including greenhouse farming, hydroponics, precision agriculture, and organic farming. These systems differ considerably in their technological sophistication, resource requirements, and underlying production philosophies. Greenhouse and hydroponic systems employ controlled environments and soilless cultivation techniques to maximize yield stability and resource-use efficiency [12,13]. Precision agriculture integrates digital technologies and data-driven management practices to optimize the spatial and temporal use of agricultural inputs [14,15]. In contrast, organic farming emphasizes ecological processes, soil health, and reduced dependence on external inputs, often compensating for lower yields through price premiums in niche markets [16].

Despite the growing body of literature on sustainable agricultural practices, most studies assess innovations using isolated performance indicators such as productivity, water-use efficiency, or greenhouse gas emissions. Such fragmented approaches fail to capture the complex interactions among environmental, economic, and social dimensions of sustainability [17,18]. Emerging evidence further suggests that the economic viability and adoption of agricultural innovations are highly context-specific, being shaped by factors such as capital availability, market access, learning requirements, and institutional and policy support [19,20].

Evaluating technological performance alone is therefore insufficient to explain why agricultural innovations are adopted and how they diffuse over time. Addressing these limitations requires a systems perspective that situates agricultural innovations within broader socio-economic and institutional transitions. In this regard, the concept of niche development within STT provides a valuable framework for understanding how sustainability-oriented innovations emerge, interact with, and potentially transform dominant agricultural production regimes [21,22]. Furthermore, IDT offers important insights into the determinants and processes through which agricultural innovations are adopted and disseminated among producers [23].

The IDT provides further clarification regarding how adoption is influenced by; relative advantage; complexity and risk associated with the new technology making it possible to identify the technological capability necessary to become aligned with systemic requirements for innovation diffusion. Together, these frameworks identify technological capability and systemic alignment within an agricultural innovation as essential components for understanding both evolutive outcomes of agricultural innovations and ongoing diffusion processes within dynamic institutional and market-based environments.

To achieve this aim, the current paper uses qualitative systematic reviews of literature that adhere to a PRISMA framework and include only peer-reviewed literature published between 2003-2025, and the focus is on greenhouse/farming, hydroponics, precision agriculture and organic farming. The goal of this literature review is to assess the various sustainability measures for each of the agricultural alternatives using three areas of comparison: how sustainable is each, how profitable are the various systems, and under which conditions the systems have been adopted.

Using Synthesis of Technology Transfer (STT) and Integration of Diffusion Theory (IDT) as a model, this paper will provide an understanding of the different innovation pathways contributing to sustainability transitions in the agricultural field and under which these systems generate economically viable results. In providing these findings, authors hope to assist researchers, policy makers, and practitioners in developing context relevant and hybrid strategies that effectively achieve sustainability and farm level profitability.

Research questions

Building on the above discussion and the identified gaps in existing literature, this study is guided by the following research questions:

- **RQ1.** How do major agricultural innovation pathways greenhouse farming, hydroponics, precision agriculture, and organic farming differ in terms of environmental sustainability outcomes and resource-use efficiency across diverse farming contexts?
- **RQ2.** What really drives profitability for each agricultural innovation pathway? Honestly, it's things like stable yields, cutting costs, and earning higher prices. The thing is, these profit drivers don't work the same everywhere.
- **RQ3.** Dose IDT help explain adoption patterns? People are cautious; they watch what happens to others before jumping in. But when adoption gains momentum, diffusion speeds up, and suddenly you see innovations catch hold across the region.
- **RQ4.** Can socio-technical factors really shape the link between a technology's potential and actual profit? Policy frameworks support or block adoption, market structures decide if farmers can actually earn more, and good infrastructure makes everything easier.
- **RQ5.** Does STT give useful insights for building smarter, more flexible agricultural innovation strategies?

Together, these research questions provide a structured framework for the qualitative synthesis undertaken in this study and support a system-level assessment of agricultural innovation as a sustainability transition process rather than a set of isolated technological solutions.

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Literature Review

Greenhouse farming: High efficiency, conditional viability

Greenhouses are among the most technologically advanced methods of achieving sustainable agriculture, providing high yield stability and efficient use of resources in a controlled environment. The increasing use of artificial intelligence (AI) to control greenhouses is enabling predictive optimization of the systems used to heat, cool, and light greenhouses, thereby lowering energy consumption while maintaining production [24,25]. Despite the benefits of this approach to greenhouse efficiency, it generates large carbon footprints because of its energy-intensive operations [26].

Energy efficiency assessments reveal a core paradox; as greenhouses optimize the flow of nutrients and water, they frequently have large carbon footprints from heating, cooling, and the use of artificial light [26]. Life cycle assessments indicate that the net environmental benefit of a facility depends greatly upon the source of energy used to produce those benefits, as facilities powered by renewable energy produce 60% to 70% less greenhouse gas emissions than facilities that depend on grid energy. Tong et al. describe a "nexus approach" as an integrated view of water-energy-food interactions, making the point that sustainable greenhouse operations should be evaluated as part of a system rather than simply optimizing single resources separately [27].

The impressive potential of advanced greenhouse technologies, however, is limited by significant barriers to their adoption. Intelligent environmental control systems that utilize sensors, automated functions, and artificial intelligence typically require a great amount of specialized technical support and have very steep learning curves [28]. Comprehensive surveys examining the progression of smart greenhouses in developing nations find that although the prices of sensors have lowered, difficulty in integrating them into existing systems, insufficient data literacy among users of the systems, and inadequate infrastructure are hindering the wider adoption of these systems [29].

The profitability of greenhouses is very much determined by the contextual factors of energy costs/or labour dynamics, proximity to markets, and government and/or other incentives [30]. In general, profitability of greenhouse operations tends to depend on getting access to premium markets; on producing over a longer period of time; and, on being able to incorporate cheaper and/or renewable sources of energy. AI-enabled spectral tuning may result in very large reductions to the amount of money spent on lighting; however the majority of the time, the payback period of the application will fall well beyond what is acceptable for conventional agricultural financing [25]. Therefore, greenhouse farming could be best understood as not an infinitely scalable solution, but rather a niche based innovation with success in respect to favourable institutional and economic lines.

Hydroponics and vertical farming: Resource efficiency without economic robustness

As compared to traditional land-based farming, hydroponic systems utilize water far more efficiently, using over 90% less water [31]. Vertical hydroponics can produce much larger yields on smaller amounts of square footage and work well in urban areas where land is limited [32]. Systematic reviews of the operational benefits of hydroponics document the conservation of water , the elimination of pesticides, the production of crops all year, and the proximity to consumers; however, the energy intensity, high capital investment, and small variety of crops produced are cited as some of the drawbacks [32,33].

Hydroponics are generally very sensitive to energy prices, how well the hydroponic system is running, and when the price of the materials going into the crops fluctuate [31]. Continuous monitoring and corrective actions for temperature, light, and root-zone conditions are required for plant factories; if there is interference to any of these three factors, it can lead to rapid deterioration of crops. New growing mediums are being developed and the substrate that is used for growing hydroponic crops can have a big impact on the way that nutrients are delivered, the way that water is held, or how much oxygen is getting to the roots. However, there is still no general agreement on which growing medium will work best for which crop.

Long-term evaluations of profitability in hydroponics vary based on climatic or socio-economic conditions. Hence, technically, the efficiency of hydroponics appears consistent; however, it is not economically viable [34,35]. As for smart hydroponics integrated with IoT, challenges include issues of connectivity and cost [36]. Although vertical farms are technologically feasible to build, there are structural, permit-related, and insurance-related barriers to overcome before a vertical farm can be established successfully [37]. In order for hydroponics to be economically viable, growers would need to produce and market high value crop products directly to end-consumers with production areas large enough (usually 1,000 square meters or more) to amortize their overhead costs [38].

Precision agriculture: Incremental gains, uneven diffusion

Precision agriculture is proving to be highly effective in minimizing waste from inputs (i.e. seeds, fertilizers, crop protection chemicals, pesticides and fungicides) and improving the efficiencies of resources such as water, especially on larger-sized commercial farms. For example, soil moisture sensors and weather-based irrigation scheduling together can decrease the amount of water used by 25% to 40% but still provide acceptable to even higher than typical yields [39,40].

The enhancement of capabilities of precision agriculture by utilizing artificial intelligence (AI) and machine learning (ML) is an area of major growth in this sector [41]. Current AI/ML applications within precision agriculture include: crop disease prediction; yield prediction; autonomous equipment operation; and optimization algorithms. Neural networks have also been found to have greater than 90% accuracy for identifying pests/diseases based on mobile phone images, allowing for timely action by growers [42]. AI/Machine-learning based climate smart precision agriculture is producing some positive results with respect to yield prediction and decreasing risk but does have some challenges; such as growers' concerns regarding data privacy and licences, platform dependencies with other growers vs proprietary systems, and liability for errors/malfunctions in AI-created algorithms [43].

The access to digital technologies for smallholder and resource-poor farmers is limited by high initial investment requirements, a lack of digital infrastructure, and data governance issues [44,45]. The cost of sensors has significantly decreased (from more than $500 per unit to

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between $50 and $100 per unit) but there is a shortage of technical support in rural areas that is necessary for setup, calibration, maintenance and interpretation of data from sensors [46]. This results in a "last-mile" issue, where the existence of technology does not equate to its effective use.

To implement IoT-based systems in precision agriculture, existing extension services, credit mechanisms and farmer organizations will need to be reimagined to facilitate collective learning and resource sharing. Small farmers, particularly smallholders, have difficulty justifying investment and developing expertise when acting alone. Consequently, the benefits of these systems will be disproportionately realized by well-capitalized farmers in areas with strong digital infrastructure and institutional support [47].

Organic farming: Ecological strength, economic ambiguity

Organic agriculture provides strong contributions to improving soils, biodiversity and long-term resilience. Long-term field trials demonstrate how conservation farming methods have improved the health of soils and maintained crop yields in even the face of climatic change - organic farming systems exhibited greater resilience to increased temperatures and drought than conventional farming systems [48]. There is a growing body of research to support the use of agroecological and organic farming approaches to develop healthy soils. For example, populations of earthworms, beneficial nematodes and other soil fauna increased by approximately two to five times in organic farming systems and contributed to improved nutrient cycling and pest control [49]. In addition, people are developing new types of organic fertilizers, using cover crops to improve soil structure and reduce soil erosion. As determined through the analysis of global greenhouse gas emissions, organic farming and conservation tillage are strategies that can be implemented to substantially reduce greenhouse gas emissions and contribute to a more sustainable form of agriculture by providing an important sink for carbon (estimated 0.5 - 1.0 Gt CO_2e/yr) and a means to reduce emissions associated with the production of synthetic fertilizers [50]. However, to unlock the full potential of climate mitigation by organic farming and conservation tillage will require supportive policies, which include systems to create carbon markets where farmers can receive compensation for providing carbon sequestration services.

Certification costs, transition risks and market volatility are all factors that are frequently overlooked when assessing profitability. While using biological inputs may significantly lower the cost of purchased inputs, the amount of labour required may increase by as much as 20-50% for certain activities such as hand weeding, composting and mechanically controlling pests [51]. When organic production is scaled-up without an increase in demand commensurate with the volume of products being produced, the erosion of the premium on organic products will occur and the economic rationale for conversion will be weakened.

Organic agriculture must address scalability concerns while maintaining their ecological integrity in the 21st Century. To do this, institutional innovations (e.g. cooperative certification systems, direct marketing channels and policy support for the transition period) will be required to develop a successful system. The success of organic agricultural systems will depend upon alignment of values, access to markets, support services and farmers' willingness to accept the risk of not achieving yield during the multi-year transition period.

Identified gaps and research direction

This critical analysis of three associated shortfalls includes firstly there is virtually no system level compares of sustainable agricultural innovation pathways & their corresponding long-term economic returns(profitability), as well as an assessment of the actual adoption dynamics associated with those pathways; secondly within existing studies there are serious deficiencies regarding assessments of the time related trade-offs between short term profitable returns versus longer term resilient returns; and finally integration of socio-technical and diffusion perspectives into achieving a better understanding regarding how institutional alignment mediates the relationship between technological performance and achieved profitability are all lacking.

Addressing these shortcomings requires a shift away from evaluation methods based on maximizing efficiency. Instead, it necessitates a new analytical approach that constructs a holistic, dynamic, and transformative analysis of agricultural innovation processes, grounded in a comprehensive analysis of socio-technical transformation theory and IDT. For example, PRISMA established the foundation for this new agricultural innovation analysis method, using agricultural innovation in the United States and Canada as case studies to systematically analyze the systemic transformation processes of agricultural innovation in these two countries.

Research Methodology

Review design and reporting standard

For this study, we conducted a systematic literature review (SLR) that was designed based on the principles outlined in the PRISMA reporting framework. This helps ensure the study's identification, screening, eligibility assessment, and synthesis processes are transparent, rigorous, and reproducible. PRISMA was originally designed for quantitative meta-analyses but is now increasingly being utilized for qualitative and theory-driven systematic reviews, especially in the fields of sustainability and social-technical transition. Therefore, this review also used an adapted version of PRISMA, with an emphasis on structured selection and qualitative rather than quantitative synthesis.

Theoretical orientation

The analysis has a theoretical underpinning based upon two distinct theories: the STT, as noted by Geels, and the IDT, as described by Rogers [22,23]. Both theories were supportive in developing the research objectives, data extraction categories, and the synthesis through interpretation. Agriculture innovation indicators were analyzed as either niche or regime aligned transitions within a wider socio-technical system using STT, while IDT provided useful analytical perspectives to understand adoption, perceived profitability, and barriers to diffusion at the farm level.

Information sources and search strategy

A broad literature search was performed across major academic databases (Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar) from 2003 until December 2025 to capture the body of work being done within sustainable agricultural innovations, specifically

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early foundational work and newly published research.

At the beginning of the search, terms were developed through an iterative process that included using Boolean operators to combine core keyword(s) as follows: "greenhouse farming", "hydroponics", "precision agriculture", "organic farming", "sustainable agriculture", "resource efficiency", "profitability", "technology adoption" and "climate-smart agriculture".

The reference lists of major review articles were also manually searched to identify other relevant studies.

Eligibility criteria

We utilized predefined exclusion and inclusion criteria (aligned with PRISMA recommendations) to select the studies reviewed. These criteria included empirical studies published in peer-reviewed journals/books/authority-review papers focusing specifically upon one of the four areas of Agricultural Innovation i.e., Greenhouse Farming, Hydroponic Farming, Precision Farming and Organic Farming; inclusive of at least one of the following attributes: examined; has created an environmental sustainable solution for use; provided an economic performance measure (e.g., net present value); examined how profitability relates to each of these four areas of Innovation with special emphasis placed upon their adaptability, and diffusion; and were completed prior to the final search date.

Studies were included if they had been completed on a field, as opposed to being restricted to a laboratory experiment and were only studied in a comparative, theory-based way. There were no restrictions relative to developments or resource-constrained areas; or that the studies were only published in English. However, studies were not included for those studies that were solely based on laboratory experiment with no application to the field/act of system or that only provided evidence of a Technical Design, or were/are opinion-pieces, editorial articles and published in sources other than peer-reviewed publications with analytical rigor; and all duplicate records across the research databases have been removed from the overall results reported herein.

Study selection process

Following the PRISMA framework, four steps made up the research selection process: identification, filtration, eligibility assessment, and decision to include. For this project, the initial search provided 1642 records from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. In addition to this, 38 additional records were found through manual review of reference lists. Therefore, 1680 records were collected in total. Out of those 1680 records, there were 412 records that were duplicates of each other. This left a total of 1268 studies to be screened by title and abstract, of which 1005 (79%) were excluded because they were unrelated to agricultural sustainability/profitability/adoption dynamics. Therefore, 263 full-text articles were assessed for inclusion based on eligibility, but 177 studies were excluded (66%) at this stage due to lack of economic analysis, only laboratory studies, or lack of system level relevance. As a result, 86 peer-reviewed studies met all inclusion criteria and were included in the qualitative synthesis of this project.

Data extraction

The procedure for data extraction used a systematic approach to ensure the data's consistency and transparency. This was achieved by using qualitative and contextual information extracted through typologies of agricultural innovations and the technology's characteristics, cropping patterns and the scale of application, environmental sustainability impacts, indicators of resource-use efficiency, investment needs and cost of operation, profit mechanisms (by reducing costs, providing stable yields and through the provision of premium prices), and barriers to adoption. The extracted data were grouped together into tables and matrices to make possible comparative analyses across studies.

Data synthesis

The qualitative thematic analysis used a PRISMA-style method to follow PRISMA rules for a non-quantitative review. First-order themes were generated through induction and second-order themes were constructed by interpretation of the literature using STT or IDT. Identifying innovations as niche, regime-compatible, or transitional was possible, as was assessing the impact of profitability on the rate of diffusion and long-run sustainability.

The different types of analysis carried out demonstrated a trade-off between efficiency and up-front capital investment, short-run profit and long-run resiliency, and technological effectiveness and institutional preparedness.

Risk of bias and quality considerations

Although formal statistical assessments of risk of bias could not be performed because of the qualitative and heterogeneous nature of included studies, methodological quality was determined by the following: restricting studies to peer-reviewed articles; cross-validating results from multiple studies or contexts; and theoretical triangulation using either the STT or IDT frameworks. These criteria increased the reliability of interpretations and helped minimize the impact of individual and context-specific findings.

Limitations of the methodology

PRISMA alignment provides better transparent reporting but also limits generalizability/statistical analysis for causal inference because study evaluations were based on qualitative methods. Results may include the insights generated by identifying patterns of results instead of effect size estimates with certainty about directional or causal relationships. However, this type of evaluation is appropriate when examining sustainable transitions for agriculture and understanding how adoption behaviors occur as well as profitability trends for agricultural items/production.

Results

Several definitions of agricultural innovations have been developed over time. More recently, there have been changes in definitions to continue to improve our understanding of the role that agricultural innovations play in rural development throughout Asia. Based on the range of facts collected from the various sources a number of general characteristics of each innovation were identified: the type(s) of agricultural

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innovation(s); the technological characteristics; the crop(s) grown and how they are managed; environmental sustainability outcomes; indicators of resource use efficiency; investment requirements and operational costs; profitability mechanisms (cost reductions; stability of yields; price premiums etc.); and barriers to adoption (Table 2).

Table 2. SLR Table for greenhouse agriculture.

Methods/ Technique used in agriculture	Processes	Crop pattern	Sustainability	Efficiency/ Performance	Investment/ Resources	Output (Profitability mechanisms)	Adoption barriers
Organic farming, zero tillage, manure application [52]	Soil carbon sequestration assessment	Mixed cereals, pulses	Enhances SOC, reduces GHG	Field trials show fertility gains	Labor and organic inputs	Higher yields, improved soil	Industrialization offsets gains
Controlled-environment greenhouses [53]	Climate control, fertigation automation	Tomatoes, cucumbers	Lower water/pesticides	Year-round uniform yield	High capital cost	Consistent quality and yield	High energy demand
Biochar + compost application [54]	Carbon management in greenhouse soils	Vegetables, cereals	Nutrient recycling and sequestration	Improves microbial activity	Biochar facilities required	Reduced fertilizer demand	Costly production/transport
Hydroponic integration in greenhouses [55]	Soil-less nutrient solution delivery	Leafy greens	Saves land/water, avoids soil degradation	Faster growth cycles	Cost of solutions and monitoring	High yield per m²	Nutrient imbalance risk
Renewable energy-powered greenhouses [56]	Solar, geothermal heating	Fruits and vegetables	Lower carbon footprint	Better energy-use ratio	Renewable infra investment	Lower energy bills	High upfront costs
Precision irrigation and fertigation [57]	Drip irrigation with sensors	Tomatoes, peppers	Reduces water/fertilizer waste	Improves WUE by 40%	Sensor network and drip lines	Uniform crop size, better quality	Requires skilled operators
Vertical greenhouse farming [58]	Multi-layer crop cultivation	Leafy greens, herbs	Saves land, lowers transport emissions	Higher yield per area	LED lighting and racks	Year-round supply	High electricity consumption
Integrated pest [59]	Biological control, reduced pesticides	Cucumbers, capsicum	Eco-friendly pest control	Reduces crop losses by 20–30%	Training and bio-control inputs	Lower pesticide residues	Monitoring intensive
Aquaponics-based greenhouses [60]	Fish-plant symbiosis nutrient cycling	Lettuce, basil + tilapia	Circular nutrient reuse	Improves productivity	Tanks, pumps, monitoring	Dual output: fish and plants	Complex management system
Climate-smart greenhouse tech [61]	Adaptive shading, ventilation models	Roses, vegetables	Improves microclimate resilience	Reduces heat stress	Shading nets, software	Higher flower/crop quality	Requires real-time monitoring
Smart sensing and IoT monitoring [62]	Wireless sensors for temp, humidity, nutrients	Tomato, lettuce	Optimizes inputs	Real-time data improves precision	IoT devices and connectivity	Increased yield predictability	Connectivity and data privacy issues
CO_2 enrichment systems [63]	Supplementing CO_2 in greenhouses	Tomatoes, peppers, roses	Enhances photosynthesis	Yield increase 20–30%	Gas supply infrastructure	Higher biomass, improved quality	Expensive gas input, risk of leakage
Nanotechnology in greenhouse inputs [64]	Nano-fertilizers and nano-pesticides	Vegetables, fruits	Reduced chemical load	Higher nutrient uptake	Costly nanomaterials	Improved growth and pest control	Long-term ecological risks
Robotics and automation [65]	Autonomous harvesting and monitoring robots	Tomatoes, cucumbers	Labor-saving, reduces waste	Increases harvest speed and precision	High capital for robotics	Efficient, uniform harvesting	High maintenance costs

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Table 3. SLR table for hydroponic agriculture practices.

Methods/ Technique used in agriculture	Processes	Crop pattern	Sustainability	Efficiency/ Performance	Investment/ Resources	Output (Profitability mechanisms)	Adoption barriers
Nutrient Film Technique [66]	Thin nutrient film circulated over roots	Lettuce, spinach, basil	Water saving; low chemical leaching	High nutrient-use efficiency	Pumps, channels	Rapid leafy growth	Susceptible to pump failure
Deep Water Culture (DWC) [67]	Roots suspended in aerated nutrient solution	Lettuce, kale	Minimal water use	Fast growth due to oxygen availability	Aerators, tanks	High yields in short cycles	Risk of root diseases
Ebb and Flow [68]	Periodic flooding/draining of root zone	Herbs, ornamentals	Reduces water waste	Good for diverse crops	Trays, pumps	Consistent yields	System complexity
Aeroponics [69]	Roots misted with nutrient spray	Leafy greens, potato	Saves >90% water	Accelerates root oxygenation	High-tech misting system	High growth rate	High energy and maintenance
Wick system (simple hydroponics) [66]	Passive capillary nutrient uptake	Herbs, small plants	Low-resource and eco-friendly	Low efficiency	Minimal cost	Suitable for small-scale	Not suitable for large crops
Kratky method [70]	Static non-circulating hydroponic setup	Lettuce, leafy greens	No electricity, low input	Good for small-scale farmers	Containers, nutrient mix	Low-cost yields	Limited scalability
Vertical hydroponics [71]	Multi-layer hydroponic towers	Leafy greens, strawberries	Saves urban land	Increases yield per m²	LED lighting, racks	High density yield	High energy demand
Hydroponic + aquaponic hybrid [72]	Fish waste as nutrient source	Lettuce, basil + tilapia	Circular nutrient cycling	Sustainable dual system	Fish tanks + hydro setup	Fish + plant production	Complex nutrient balance
Smart hydroponics with IoT [73]	Sensors and automation	Tomatoes, leafy greens	Optimizes water/fertilizer	Precision control increases yield	Sensors, automation	Consistent quality	Connectivity and cost issues
Hydroponic fodder production [74]	Sprouting grains in trays	Barley, maize for livestock	Saves land and water	Short-cycle fodder ready in 7–10 days	Trays, water system	Fresh green fodder	Low dry matter yield
CO_2 enrichment in hydroponics [63]	Adding CO_2 to hydroponic greenhouses	Tomato, cucumber	Improves photosynthesis	20–30% yield increase	CO_2 supply	Higher fruit biomass	Cost of CO_2 input
Nanofertilizer-based hydroponics [64]	Nano-nutrient delivery	Vegetables, fruits	Reduces chemical waste	Higher nutrient absorption	Nanomaterials	Improved plant growth	Long-term ecological concerns
Climate-smart hydroponics [75]	LED lighting, controlled environment	Leafy greens	Energy-efficient	Extends production to urban areas	LED + control systems	Year-round production	High energy bills
Hydroponics with renewable energy [76]	Solar-powered hydroponics	Vegetables, herbs	Carbon neutral	Improves energy-use ratio	Solar panels, pumps	Cost-saving in long-term	High upfront investment

Table 4. SLR table for precision agriculture.

Methods/ Technique used in agriculture	Processes	Crop pattern	Sustainability	Efficiency/ Performance	Investment/ Resources	Output (Profitability mechanisms)	Adoption barriers
GPS-guided variable rate application [77]	Adjusting fertilizer/pesticide rates spatially	Corn, wheat	Reduces chemical overuse	Improves nutrient-use efficiency	Requires GPS, sensors	Higher yields with less input	High initial cost
Remote sensing and UAV imaging [78]	Crop monitoring via drones	Vineyards, wheat	Reduces water and input waste	Real-time detection of stress	UAVs, multispectral cameras	Early disease detection	Data analysis complexity
IoT-enabled smart irrigation [62]	Soil moisture and weather-based irrigation	Vegetables, cereals	Saves >30% water	Increases WUE	IoT sensors, connectivity	Reduced water bills	Connectivity gaps in rural areas

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Precision seeding with robotics [79]	Automated planting at variable density	Maize, soybean	Ensures seed optimization	Enhances germination success	Robotics, automation	Consistent emergence	High capital requirement
Yield mapping and GIS [14]	Collecting spatial yield data	Corn, soybean	Identifies soil health patterns	Improves resource allocation	Yield monitors, GIS	Field-specific fertilizer plans	Data management complexity
Hyperspectral imaging for disease detection [80]	Non-invasive crop health monitoring	Wheat, sugar beet	Reduces pesticide use	Enables early stress detection	Spectral cameras	Healthy crops with reduced sprays	High equipment cost
Blockchain-enabled supply chains [81]	Traceability of agri-products	Mixed crops	Enhances transparency	Reduces fraud and losses	Blockchain infrastructure	Safer and trusted food	Regulatory and adoption issues
Automated fertigation [32]	Nutrient delivery via IoT and automation	Tomatoes, cucumbers	Reduces fertilizer leaching	Optimized nutrient cycles	Fertigation system	Higher crop quality	Power and sensor dependency
Variable rate irrigation [82]	Adjusting irrigation by soil/crop need	Cotton, maize	Improves water sustainability	Boosts irrigation efficiency	Sprinklers, pivot control	Optimized yield per unit water	Complex setup
Climate-smart PA with AI models [15]	AI for yield forecasting and risk reduction	Wheat, rice	Improves resilience to climate variability	Better predictive accuracy	AI tools, datasets	Informed decision-making	Data privacy and skill barriers

Table 5. SLR table for organic farming / agriculture.

Methods/ Technique used in agriculture	Processes	Crop pattern	Sustainability	Efficiency/ Performance	Investment/ Resources	Output (Profitability mechanisms)	Adoption barriers
Compost and farmyard manure application [83]	Regular application and incorporation of compost/manure; microbial activation and slow nutrient release	Cereals, vegetables, mixed rotations	Improves soil organic C, microbial diversity, water holding capacity	Maintains soil fertility though yield gaps vs. conventional may exist	Moderate: labor and compost production/storage facilities	Better soil health, improved resilience to drought; improved produce quality	Nutrient supply slower than synthetic fertilizers; bulkiness and logistics
Yield comparison of organic vs. conventional practices [84]	Meta-analysis of yield data across systems	Various crops globally	Organic more sustainable in resource use	Average yields ~20% lower than conventional; varies by crop	Variable: depends on context and inputs	Demonstrates potential for sustainable systems with reduced input	Yield gap remains key limitation for scaling
Crop rotation and diversified rotations [16]	Planned legume–cereal–vegetable sequences	Cereal–legume–vegetable	Enhances biodiversity, reduces disease/pests	Can sustain yields, reduce input needs	Low–moderate: seed diversity, planning	Stable yields across seasons; reduced pest pressure	Requires careful planning and market linkages
Cover crops and green manures [85]	Grown in fallow/between main crops; incorporated	Cereals, vegetables	Improve soil structure, reduce erosion, increase C sequestration	Improve nutrient cycling and water retention	Low–moderate: seed, extra field ops	Soil health gains, weed suppression, yield improvement	Opportunity cost of land/time; management complexity
Biological pest control and IPM [86]	Habitat manipulation, biocontrol, pheromones, botanicals	Vegetables, orchards, cereals	Reduces pesticide use, promotes ecosystem services	Can reduce pest damage and residues; requires knowledge	Low–moderate: training, monitoring, biocontrol agents	Reduced pesticide residues; long-term pest suppression	Requires skilled monitoring; variable performance
Agroforestry and ecological integration [87]	Trees + crops/livestock; alley cropping	Annuals + perennials	Increases biodiversity, carbon storage; resilience	Enhances long-term productivity and efficiency	Moderate–high: tree planting, delayed returns	Diversified outputs, ecosystem services	Long time to benefits; land tenure issues

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Reduced tillage in organic systems [85]	Minimal disturbance + mulches and cover crops	Cereal/ mixed croppin g	Reduces erosion, saves fuel	Maintains soil structure, lowers energy use	Moderate: specialized equipment	Soil conservation, stable yields	Weed management harder without herbicides
Organic greenhouse cultivation [16]	Controlled environment with organic inputs	Vegetab les, herbs, orname ntals	Efficient water use; reduced pesticide residues	High per-area productivity	High: greenhouse structures, organic inputs	Premium produce, season extension	Higher cost, certification challenges
Legume intercropping and N fixation [83]	Intercropping legumes with cereals	Cereals + legumes	Provides biologically fixed N	Improves N supply, increases productivity	Low–moderate: seed, management	Reduced fertilizer use; stable yields	Competition between intercrops
Market and certification practices [85]	Certification compliance, traceability	All organic crops	Price premiums, consumer trust	Economic viability if premiums accessible	Moderate: certification cost, audits	Premium prices, wider adoption	Certification costs/time; premium varies

The Tables 2 to 5 show the major differences in terms of suitability, efficiency, investment requirements, and sustainable outcomes. The various approaches, from greenhouse-based methods (Tabel 1), hydroponic-based methods (Table 2), precision agricultural methods (Table 3), and organic farming methods (Table 4), demonstrate both opportunities and challenges of today's farming models as well as mechanisms for generating output and profit.

Method-wise comparisons and crop patterns

Techniques for greenhouse agricultural production, including climate-controlled conditions and CO2 enhancement, are suitable for producing high-value crops (for instance, tomatoes, cucumbers, and roses) [63,79]. Hydroponic systems are also effective production methods for growing leafy greens (e.g., lettuce, spinach, and basil) through use of the nutrient film technique (NFT) and deep water culture (DWC) [66,67]. Precision agricultural methodologies such as GPS-based application and UAV imaging technologies have been widely employed for cereal grains and large-scale, commercially produced crops like wheat, maize, and soybean [77,78]. Organic agriculture emphasizes crop rotation and diversification by growing legumes, small grains, and vegetables which contribute to maintaining biodiversity and soil quality [16,83]. As a result, while greenhouse and hydroponic types of growing systems are primarily focused on the horticultural sector, precision agricultural and organic farming systems have a more universal application for both types of production that occur on land.

Suitability and efficiency (performance)

Whether urban or peri-urban, the suitability of a system for agriculture is determined by scale and environmental conditions. Both hydroponics and greenhouses offer high efficiencies for water usage hydroponics can save up to 90% of the amount of water required for growing in soil [69]. Precision irrigation systems are also able to increase WUE over 30% when used in conjunction with traditional irrigation systems [62]. Organic agriculture has been shown to promote environmental resiliency through the addition of soil organic carbon and greater microbial biodiversity, despite producing an average of 20% lower yields than conventional systems [84].

Investment requirements and output

The financial component is still a significant issue for investment purposes. Controlled-environment greenhouse farming (CEGF) and vertical farms require a large overall capital investment to develop the infrastructure (building, LED lights, etc.), and the production of a reliable supply of high-quality vegetables takes years of consistency all season [58]. Hydroponics and aquaponics also have a large capital investment for the purchase of tanks, pumps, and monitoring devices, which produce a large amount of produce per square foot of growing space and have the added benefit of producing both fish and produce with aquaponics [60]. Precision agriculture is considered to be capital intensive (higher capital cost), but due to employing space-optimizing practices, a farmer using precision agriculture will see very high productivity gains in the long term along with a decrease in the amount of inputs being used for each unit of production [14]. Organic growing systems require a low capital investment but have high labor and management costs and therefore typically provide ecological benefits as well as yield higher prices in the open market [16].

Adoption barriers

All of the above-mentioned techniques have their own distinctive advantages, including for example the greenhouse and hydroponic farms being especially effective in land-scarce or water-scarce environments; while providing climate change resilience; to better help make (more informed) decisions about how to farm, such as through the use of precision agricultural methods [15]. As well, despite this, organic farming is still critical for providing ecoservice benefits; building trust between consumers and producers (through organic certifications); maintaining biodiversity [85]. Nevertheless, all methods do have some limitations, namely greenhouse farming has high energy/operating costs along with high start-up costs (i.e., construction); hydroponic crops can become highly unbalanced in nutrient levels or systems can go down causing the inability to grow crops; precision farming has limiting factors with the complexity of data being needed in addition to limited infrastructure being available for rural areas; and organic growers must operate under yield gaps associated with growing crops organically, plus incur extra costs associated with obtaining organic-certification labels [56,68,82,84].

Discussion

The findings of this literature review reflect an interpretation of the STT which suggests that sustainable agricultural innovations are not simply technical substitutes for conventional agricultural practices, but rather represent part of a larger socio-technical system that is made up of technologies, markets, institutions, knowledge networks, and

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cultural norms. Innovation niches such as greenhouse and hydroponic farming, precision agriculture, and organic farming all exist in parallel with conventional agriculture, but their success and failure depend on their ability to align with or change the production methods, markets, and policies of the overall agricultural production regime.

When viewed through the lens of STT, controlled-environment production systems (greenhouse and hydroponics) are examples of high-performance niches that produce greater resource efficiency and yield stability than conventional agriculture; however, their diffusion into conventional farming systems is impeded by a lack of alignment with existing energy; financial; and risk sharing infrastructures, especially in developing markets. Although these niche production technologies can provide attractive financial returns from premium prices; year-round production; and predictable yields, their financial viability is contingent on access to capital; reliable energy infrastructure; and supportive institutional structures. Therefore, profitability is generated not by the individual niche technologies, but by their integration into the overall socio-technical regime surrounding agricultural production.

In the socio-technical landscape, precision agriculture occupies a transitional intermediary position and therefore does not disrupt the prevailing system but incrementally realigns existing agricultural systems by embedding digital intelligence into traditional practices. Precision agriculture corresponds to the STT framework of regime reconfiguration through productivity gains and profit improvements through efficiency improvements rather than through structural replacement. The literature reviewed shows that precision agriculture increases profit by decreasing input costs, regulating water and fertilizer application, and lessening climate variability. However, adoption is irregular due to a lack of appropriate skills, struggles with data governance, and a lack of digital infrastructure; thus, technology alone does not ensure an adequate return on investment.

Organic agriculture represents an alternative transition path using normative and institutional means rather than technological means. Organic agriculture has a high dependence on social values, certification systems, consumer confidence, and price premium; therefore, organic agriculture cannot be maximized like other forms of agricultural production. Organic systems generally have lower yield productivity relative to other systems, but the literature indicates that organic systems have higher potential profitability over time than other systems due to lower input use, improved soil productivity, and access to differentiated markets. Consequently, this suggests that profitability must be viewed as an evolving concept in sustainability transitions.

IDT provides insights into the relationships between sustainability, adoption rate, and profitability across the four agricultural approaches as they relate to each other. Hydroponics and precision irrigation have high likelihoods of adoption because they are perceived as having large relative advantages (e.g., water savings for hydroponics; lower costs for precision irrigation). Low observability, limited trialability, and high complexity for both of these technologies, however, slow their diffusion to small holders.

Greenhouses and hydroponics may both produce favorable economic results, but their diffusion is hindered because the economic benefits of profitability will neither be immediately observable nor reversible if their use does not result in expected profits. Organic agriculture has a low degree of technical complexity; however, it has been slow to diffuse because the time lag for obtaining returns is long and there is uncertainty as to whether organic products will receive premiums in the market.

Thus, qualitative synthesis of the four agricultural approaches points out that while profitability is a necessary prerequisite to farm or grow food, it is not sufficient on its own; risk and the exposure of risk, learning and education, institutional support, and compatibility with current farming practices are also major factors influencing farmers' decisions regarding the adoption of innovative production methods and practices.

As a result of farmers being able to evaluate new production methods or practices based on all of the factors influencing their decisions, hybrid production configurations, such as organic agriculture using precision-enabled technologies and greenhouses powered by renewable energy, have been developed whereby the risk of adopting new production methods was minimized while retaining appropriate economic incentive for the farmer. These hybrid configurations illustrate IDT and STT by demonstrating the importance of both a gradual shift towards a new regime and an effort to establish a lower threshold for farmers to adopt new sustainable practices and methods of agricultural production.

Table 6. Comparative matrix of agricultural methods.

Agriculture Method	Typical Crop Pattern	Suitability	Efficiency / Performance	Key Advantages	Major Limitations	Investment Required	Output Characteristics
Greenhouse Farming	Tomatoes, cucumbers, roses, herbs	Urban and peri-urban areas; high-value horticulture	Very high yield per unit area; year-round production	Continuous supply, premium-quality produce, reduced pesticide use	High capital requirement; energy-intensive climate control	High (structures, LED lighting, climate-control systems)	Uniform, premium-quality crops; reliable output
Hydroponics	Leafy greens, lettuce, basil, strawberries	Land-scarce, water-constrained, urban settings	~90% water savings; rapid growth cycles	Efficient water use, high-density production, urban adaptability	Pump failure risk; nutrient imbalance; costly inputs	Moderate–High (tanks, pumps, automation systems)	High-density yields; potential dual outputs in aquaponics
Precision Agriculture	Cereals (wheat, maize, soybean), vineyards	Large-scale farms; variable soil and climate conditions	30–40% water savings; optimized input application	Input efficiency, climate resilience, data-driven planning	High setup cost; data complexity; rural connectivity gaps	High (GPS, sensors, UAVs, AI and analytics tools)	Higher yields with reduced input waste

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Organic Farming	Cereals, legumes, vegetables, orchards	Sustainability-driven, biodiversity-focused farming	Improved soil fertility; long-term resilience; ~20% lower yields	Eco-friendly, enhanced biodiversity, strong consumer trust	Yield gap vs. conventional farming; certification costs	Low–Moderate (labour, compost, certification)	Premium-priced produce; improved soil health and ecosystem services

Table 6 shows the comparative matrix allows for a comprehensive comparison of agricultural techniques according to important criteria like crop type, potential site, efficiency, financial investment, yield, pros, and cons of each agricultural system. The comparison of greenhouse farming with hydroponic systems, precision agriculture, and organic farming allows the identification of both similarities and differences between agricultural methods. For example, while greenhouse farming produces the highest-quality crops year-round, the costs associated with greenhouse production (including the needed capital and energy) limit its implementation [53,56]. Hydroponic systems conserve substantial amounts of water (as much as 90 percent), and produce high yields per unit area, but rely on a variety of technical factors for successful production and can be subject to failures in pumps or in nutrient relationships [66,67]. Precision agriculture improves the efficiency of input use and increases agricultural producers' ability to adapt to changing climatic conditions. However, precision agriculture has significant start-up costs and requires a great deal of data to implement successfully (Figure 1) [14,77]. In contrast, organic farming requires lower levels of investment, provides both environmental and market benefits; however, conventional agriculture continues to provide approximately 20 percent greater yields than organic agriculture systems [83,84]. Therefore, use of the matrix allows for a more detailed analysis of how efficient use of inputs and sustainable agricultural production can be improved through conserving certain resources (Figure 2).

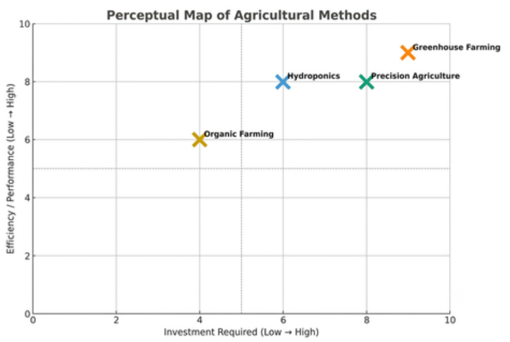

Figure 1. Perceptual mapping of agriculture innovation and profitability.

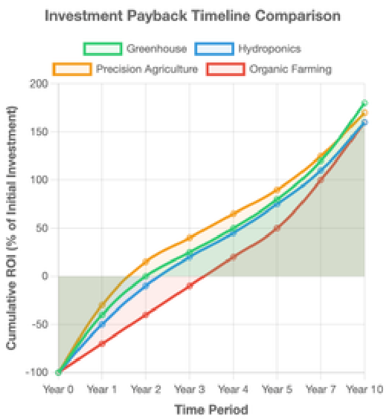

Figure 2. Investment payback timeline.

Table 6 shows how the three agricultural methods can be compared side by side with a perceptual map (Figure 1) that portrays a strategic view of their position on two dimensions, the amount of investment needed to produce them and the degree of efficiency they achieve, therefore indicating results. In the chart, greenhouse and precision farming are in the same quadrant of high investment and high efficiency, suggesting that these two methods are the best opportunity to maximize productivity in high resource use environments. Hydroponics has moderate to high investment levels and similar efficiency making it a viable agricultural method in areas where traditional farming is less feasible [69]. The comparison chart (Figure 2) shows that organic farming has low to moderate investment and moderate efficiency which speaks to the ecological benefits and affordability of the method, but also highlights the challenges associated with scaling [49].

Overall, the use of the comparative matrix and perceptual mapping provides strategic perspective regarding how sustainability outcomes result from the amount of investment used and the context in which the method has been applied. The findings do not conclude that one type of agricultural method is better than another; rather, they demonstrate the varied positions of the agricultural methods on both the technological and ecological dimensions [22]. This provides an opportunity to use hybrid adoption models, such as the use of renewable energy in controlled environments or the integration of ecological methods into precision agriculture [66].

Conclusion, Theoretical and Profitability-Oriented Implications

Combining IDT and STT produces a systemic view of how agricultural innovations become more sustainable by focusing on the transition rather than the direct substitution of technology.

No one pathway will optimize sustainability and profitability of agricultural innovations; however, the proper conditions to facilitate the emergence of sustainable agricultural innovation are established through an interaction of technological capability, institutional capacity, and the market.

From a theoretical perspective, the findings support the notion that the performance of agricultural innovation cannot be assessed solely on the basis of performance metrics. The conditions for agricultural adoption and profitability emerge from the interactions between technological characteristics, regime stability, market incentives, and socio-institutional support.

Organic farming is an illustration of a value-based regime Transformation that is associated with long-term profitability, while precision farming is associated with efficiency-oriented regime adaptation.

Controlled-environment systems are examples of valuable potential niches; however, their ability to generate profitable growth is dependent on the structural support mechanisms in place to support the food system, including energy transitions and financial inclusion.

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The findings indicate that, for a transition to be successful (from practical perspective), there needs to be a distinct innovation pathway including policies that are complimentary such that they reduce risk, enhance the ability to learn and support market stability. Instead of being focused on single-technology approaches, policy makers and practitioners should promote hybrid approaches that incorporate elements of resilience (ecological) and precision (technical) in order to ensure farms are profitable through their investments in capacity building, creating infrastructure, developing markets and/or the use of technology.

The perceptional mapping also added visibility to the strategic positioning of these types of methods and how they are clustered with respect to investment and efficiency. Thus, the perceptional mapping is a good visual tool that allows policy makers and practitioners to look at where any of these strategies are relative to the two axes of investment and efficiency and provides an ability for them to assess the appropriateness of using those strategies. No one strategy universally dominates over another; therefore, the perceptional mapping provides information that will assist policy makers and practitioners in making decisions about the use of context sensitive strategies. For example, incorporating renewable sources of energy into greenhouse systems may reduce the energy intensity of those systems, while applying precision farming techniques may provide a degree of resiliency to organic farming operations.

There are many possible opportunities for future studies/building upon these conclusions. For instance, since organic farming is well-suited from an ecological perspective and digital agriculture offers precision than previously available, more studies should be done to determine whether a hybridized approach would yield positive results. Secondly, more quantitative research (empirical studies) needs to be completed to determine if hydroponic and aquaponic systems are economically feasible in different localities and climates, and for how long these systems will be viable. Thirdly, future research should identify ways to incorporate renewable energy sources and practices related to circular economies as a means of minimizing capital costs and operational costs associated with controlled-environment agriculture. In addition, many studies focused on policy development should also examine potential subsidy approaches, certification systems and capacity building programmes that may help to facilitate adoption; specifically, among smaller farming operations.

To summarize, progressing towards achieving sustainable agriculture will not rely on one type of agricultural practice but rather on combining many different (and varied) approaches to meet the requirements of each farmer based upon the circumstances in which they are located (i.e., geography). All of which must be enabled through a supportive technology platform, policies and financial market incentives/benefits.

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