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Transformative Innovations in Agriculture – A Framework for Shaping the Future of Farming in a Changing Landscape

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Abstract
Innovations are powerful forces revolutionizing markets and industries, particularly in agriculture. Both transformative and disruptive innovations are crucial approaches for addressing global challenges like climate change, food security, and resource efficiency. Transformative innovation creates fundamental changes, addressing large-scale challenges and establishing new paradigms, aiming for sustainable outcomes. Disruptive innovation, on the other hand, introduces simpler, often more affordable solutions that initially serve niche markets before expanding to displace established offerings. While disruptive innovations may take longer to develop initially, they typically achieve faster market penetration once deployed. Longer market reach time in the agricultural sector, relative to other industries, combined with a rapidly evolving landscape pose unique hurdles for innovation adoption, highlighting the need for a balanced approach leveraging elements of both transformative and disruptive innovation. To overcome these obstacles, we propose an advanced innovation framework, specifically tailored to food production. By examining various schools of thought, current research gaps, and future developments, we demonstrate how targeted approaches and effective implementation can sustainably address complex global challenges in agriculture. Our work offers valuable insights for policymakers, researchers, and industry stakeholders, aiming to catalyze sustainable solutions for 21st-century food production.

Keywords: Food Security, Sustainable Food Systems, Food System Transformation, Agricultural Innovation Systems, Sustainability

Introduction
Agriculture stands at a critical juncture, facing unprecedented challenges that demand innovative solutions [1]. Traditional farming practices are increasingly strained by population growth, environmental degradation, and changing consumer preferences, necessitating a fundamental transformation of our food systems [2]. Key issues such as climate change, food security, and resource efficiency as well as industry-specific challenges such as complex international supply chains, high levels of product differentiation and increasing regulatory governance have created an urgent need for innovation [3].

Transformative innovation involves significant, profound changes that create new systems or paradigms. It often addresses complex, large-scale challenges and aims for sustainable outcomes [4]. In contrast, disruptive innovation introduces simpler, often more affordable solutions that initially cater to underserved markets or niches, gradually overtaking established markets by targeting overlooked customer segments. Disruptive innovations typically achieve faster market penetration once deployed but may take longer to gain initial traction during development segments [5,6].

Both transformative and disruptive innovations have revolutionized various industries. Examples include the disruptive CRISPR/Cas method of genome editing for the healthcare sector or the transformation of fossil-based towards regenerative energy systems. However, the agriculture sector's unique characteristics, including its producer-centric focus, regulatory complexities, and environmental dependencies, present distinct challenges for implementing new technologies and practices [7-9]. Various agricultural innovation approaches on a system level have emerged in recent decades, including National Agricultural Research System (NARS), Agriculture Knowledge and Information System (AKIS), Agriculture Innovation System (AIS) [10]. However, the agricultural sector still lacks a clear framework for introducing and scaling innovations, hindering progress and adaptation [11].

The historical importance of innovation to meet our past agricultural demands underscores a similar reliance in the future. Recent data highlights the urgency of this need. In 2024, an estimated 19.0% of the population in 83 low- and middle-income countries (LMIC), or 824.6 million people, are unable to consume the 2,100 kilocalories per day considered necessary for a healthy and active lifestyle. While this represents a 27.5% decrease from 2023, the challenge remains significant [12]. Looking ahead, projections indicate a growing discrepancy between global population and food capacity. By 2050, over 12% of the population may face food insecurity, worsening to almost 18% by 2075 and affecting nearly 2 billion people by 2100 [13]. These projections consider the impact of climate change, which is expected to decrease predicted crop production by an average of 11%. The International Food Security Assessment (IFSA) projects that grain demand will increase by 2.4% across the 83 LMIC countries in the next decade, primarily due to per capita income growth in Asia and population growth in Sub-Saharan Africa. However, grain production is only projected to increase by an average of 1.7% annually through 2034, resulting in a significant shortfall in food and feed availability [12].

The present work seeks to provide a comprehensive understanding of how transformative and disruptive innovations can help to reshape agriculture to meet the demands of a changing world, by analyzing historical examples, current barriers, and future possibilities. We integrate rigorous academic research with practical industry perspectives to create a new innovation approach to specifically understand and advance agricultural innovation strategies. This advanced framework is based on elements of transformative approaches, providing a comprehensive strategy for driving meaningful changes in agriculture and society.

Transformative Innovation vs. Disruptive Innovation

Transformative innovation and disruptive innovation are two distinct yet related concepts in the field of innovation. While they share some similarities, they differ in their approach, impact, and execution. Nevertheless, many frameworks can be used for both transformative and disruptive innovations, depending on how they are applied. For example, the Innovation Ambition Matrix introduced by Nagji and Tuff (2012) can support both types of innovation, depending on the specific goals and implementation [14]. Another example is the moonshot innovation approach, that describes ambitious, groundbreaking projects or ideas that aim to solve significant global challenges. The approach is both disruptive because of its ability to create entirely new markets and transformative because of its potential to yield extraordinary rewards for both society and organizations [15].

Both transformative and disruptive innovations aim to create significant change in industries or markets. They can lead to the creation of new markets or business models. Established companies drive transformative innovation building upon existing capabilities, while disruptive innovation starts in niche markets. Another differentiating dimension is the timing of impact: Transformative innovations may take longer to develop and penetrate the market, but achieve faster penetration once deployed. Disruptive innovation, on the other hand, generally has a more immediate impact on existing markets. Regarding risks and uncertainties transformative innovations generally involve lower risk as they build on existing technologies or processes. In contrast, disruptive innovations usually involve higher risk and uncertainty given their higher degree of novelty and impact within a short time period.

Disruptive Innovation Framework: The 4-Stages

The disruptive innovation theory by Christensen (1997) is a conceptual model that describes the process by which innovative technologies or business models fundamentally change an industry by a four-stage framework [5]. This framework specifically focuses on how new entrants can challenge established firms by creating new markets or serving overlooked segments:

- Disruptive innovation starts by targeting overlooked, low-end consumers and non-consumers with accessible and novel solutions.
- Initially seen as inferior, these innovations gain traction in underserved or emergent markets.
- Through incremental enhancements, they progressively satisfy the demands of mainstream customers, driving market disruption.
- Ultimately, they move upmarket, competing directly with established players [16].

The four-stage framework provides a structured approach to understanding the lifecycle of disruptive innovations. It emphasizes the dynamic nature of disruption and the challenges faced by both incumbents and disruptors throughout the process. Recent research has expanded on this concept, highlighting the importance of business models in driving disruptive innovation [17].

Studies have emphasized that disruptive innovation is not solely about technological advancements, but can also include social or business model innovations [18-21]. Meal kit delivery services exemplify disruptive innovation in the food sector by initially targeting niche markets with pre-portioned ingredients and recipes, catering to busy consumers seeking convenience. As their business model gained traction, these companies optimized their operations and expanded offerings, capturing a significant share of the mainstream market and prompting traditional grocery retailers to adapt by introducing similar services. Kuokkanen et al. proposed that disruptive sustainable innovation focuses on "which existing functions are disrupted, or which attributes are transformed with more sustainable ones" [22]. This perspective broadens the scope of disruption to include "sustainability-driven" innovations.

A Framework of Transformative Innovation

Loorbach et al. describe transformative innovations as "socio-material", emergent, multi-actor phenomena characterized by shared ideas, objects, and activities across locally rooted sustainability initiatives [23]. These initiatives explore and develop alternatives to incumbent and perceived unsustainable regimes they seek to challenge, alter, or replace. They describe a framework of five key mechanisms through which transformative innovations develop:

- Growing: Attracting more participants or funding to increase the quantitative growth of an initiative.
- Replicating: Translating ideas and models into new contexts, often through inspiration.
- Partnering: Pooling resources and competencies between different initiatives to enhance impact.
- Instrumentalizing: Strengthening innovations by leveraging opportunities within the governance context.
- Embedding: Institutionalizing innovations through mainstreaming and structural anchoring in regulations or funding schemes.

The framework emphasizes that transformative innovations are inherently connected through translocal networks, facilitating the exchange and translation of practices and principles across diverse local contexts. This connectivity allows for the emergence of a collective transformative identity that enhances the potential for broader sustainability transitions. By focusing on the "socio-material" aspects and the mechanisms of development and diffusion, the framework provides insights into how local initiatives can engage with and influence existing structures, thereby contributing to systemic change in society [23].

Specific characteristics of agriculture that reveal unique challenges for the application of innovation frameworks

The agricultural sector faces unique challenges in adopting and implementing innovative technologies and practices:

Producer-Centric Focus

Unlike industries such as technology or retail, which are primarily consumer-driven, agriculture remains largely producer-focused. This orientation can slow the adoption of new technologies that may require significant changes to established farming practices [24,25].

Regulatory Barriers

The agricultural sector faces stringent regulatory oversight, particularly for biotechnological innovations, but also for plant breeding technologies and other agricultural innovations. Prolonged approval processes can significantly delay the introduction of new technologies, increasing costs and reducing incentives for innovation [26].

Climate Dependency

The agriculture industry is intrinsically linked to climate, with extreme weather patterns disrupting agribusiness while the agriculture, forestry, and other land use sector itself contributes about 22% of global greenhouse gas emissions [27]. Agriculture's inherent vulnerability to environmental factors adds an additional layer of complexity to innovation adoption [28].

Water Usage

High water usage poses a significant challenge for the agricultural industry as it accounts for approximately 80% of global freshwater consumption, with some developing countries reaching up to 90%. This excessive demand can lead to biodiversity loss, soil degradation, and the depletion of water resources, exacerbating existing environmental issues [29].

Low Digitalization

Compared to sectors like technology or transportation, agriculture has been slower to adopt digital innovations. This lag in digitalization can impede the implementation of data-driven technologies that could potentially revolutionize farming practices [30].

Inadequate Existing Frameworks

Existing innovation frameworks often overlook agriculture's unique challenges, highlighting the need for a tailored approach that incorporates innovative business models, enabling technologies, and value networks to benefit all stakeholders [1,31,32].

Discussion

Beyond Disruption: Reimagining Agricultural Innovation in the 21st Century

The history of agriculture has seen several transformative and disruptive innovations that have reshaped farming practices and food production. The Green Revolution, sparked by the Haber-Bosch process for producing nitrogen fertilizer, introduced high-yielding crops, synthetic fertilizers, and modern irrigation, doubling crop yields and averting famine in the developing world [33,34]. Genetically Modified Organisms and the introduction of hybrid seeds in the early 20th century also represent significant transformations in agriculture, altering crop genetics, revolutionizing farming practices, and being a promising field of agricultural innovation until today [35-37]. Additionally, regenerative agriculture practices, such as no-till farming and cover cropping, exemplify transformative innovation by restoring soil health and biodiversity [38,39]. More recently, precision agriculture technologies, greenhouse and vertical farming, and the digital revolution in agriculture have demonstrated further innovations in the sector [40-42]. These innovations often challenge existing innovation frameworks such as the transformative innovation framework or Christensen's disruptive innovation model given that despite their disruptive character these innovations have long development timelines due to scientific complexity, regulatory hurdles, and other challenges specific to the agrifood sector (see Specific characteristics of agriculture that reveal unique challenges). In addition, agriculture's connection with other sectors requires a systemic approach that goes beyond simple tech-focused models, emphasizing the need for a holistic, industry-specific innovation framework.

The development and deployment of nematode-resistant tomato rootstock technology (TRS) offers a compelling case on the complexities of introducing innovative solutions in the agricultural sector. Tracing the evolution of tomato cultivation from the 1970s to the 1990s reveals an innovation journey marked by both potential and challenges.

Initially, tomatoes were grown in soil-based heated glasshouses, yielding around 30 kg/sqm over two cycles per year. However, diseases like corky-root rot posed significant problems, driving the need for resistant rootstocks [43]. In the 1970s, De Ruiter recognized this urgency and introduced the innovative TRS to advance crop production. Yet, the lack of grafting technology at the time hindered widespread adoption, compounded by issues like large seed volumes and low germination rates [44].

The 1980s saw the introduction of substrate cultivation, reducing the necessity for corky-root resistance and leading to a decline in TRS demand, except in regions like Spain where soil cultivation continued. This rapid shift in the innovation landscape exemplifies the challenges of managing transformative innovations in agriculture [44].

The 1990s brought a tomato crisis that shifted market preferences, prompting De Ruiter to introduce the Fusarium-resistant Beaufort TRS. This period also saw the arrival of grafting technology from Japan, eventually improving efficiency in Europe. By 1998-1999, over 100 TRS successions were tested, leading to the development of the enhanced Maxifort rootstock. However, the low germination rates of this variety necessitated investments in seed technology solutions to improve adoption [44,45].

This example highlights the complex, non-linear nature of innovation processes in agriculture, which often do not align with established innovation models. The evolution of the TRS technology demonstrates the unique challenges faced by agricultural innovations, including long development timelines and rapid shifts in market preferences and cultivation practices. This exemplifies how innovations in the agrifood sector are influenced by a complex interplay of technological, regulatory, and market factors, making it difficult to apply generic innovation frameworks. Addressing these sector-specific challenges requires a more tailored, systemic approach that accounts for the distributed nature of agricultural production, the interconnectedness with adjacent industries, and the need to engage farmers as key stakeholders throughout the innovation process.

Potential Future Developments in the Field: Establishing a new Innovation Framework for Agriculture

Based on the identified differences and limitations, we propose a framework based on transformative innovation that takes into account the unique challenges of agricultural innovation. It is a "circular 5-step" innovation framework for transformative innovation in agriculture.

- **Understand and Segment Farmer Needs:** Conduct surveys to identify challenges and preferences, segment by farm size, crop type, and technology readiness.
- **Promote Participatory and Sustainable Development:** Engage farmers in co-creation, align innovations with sustainability goals.
- **Leverage Intermediaries and Provide Training:** Collaborate with cooperatives and advisory services for outreach, provide hands-on training.
- **Demonstrate Return on Investment (ROI) and Build Trust:** Communicate ROI, ensure transparent data

policies, and show how data improves farm management.
- **Foster Knowledge Exchange and Evaluate Impact:** Enable peer learning, track impact, and invest in long-term research to refine innovations.

This circular framework emphasizes the importance of continuous improvement and adaptation in agricultural innovation. After completing step 5, the process cycles back to step 1, ensuring that innovations remain relevant and effective in addressing evolving farmer needs and environmental challenges. By focusing on these changes, our comprehensive framework aims to not just improve, but work towards transforming agricultural practices to align with environmental and societal goals, which could lead to a more sustainable, resilient, and inclusive food system [46,47].

One innovation example that currently transforms vegetable farming practices in alignment with environmental and social goals is the Seminis® brand "High Rise™" broccoli series, including the Eiffel, Hancock, and Titanium varieties launched in the USA, New Zealand, Australia, and Spain in 2017. As farmers perceive the cost and availability of labor as a significant challenge, especially in crop value chains where hand harvesting dominates, Bayer made use of this innovation potential by providing growers with new varieties that could be mechanically harvested across the globe. "High Rise™" is characterized by uniform maturity, competitive yield potential, consistent product quality and clean stems. In addition, it supports harvest efficiency, which could lead to fewer harvest passes and the potential to improve crop profitability through lower labor-associated costs.

The commercial introduction of the new varieties was characterized by a widespread adoption by farmers, which has its grounds in the combination of important steps of the above-outlined innovation framework.

- **Understand and Segment Farmer Needs:** The Vegetable Seeds business of Bayer conducted farmer surveys and focused its research within the broccoli value chain on mechanisms of addressing the topics of increasing labor costs and harvest losses as well as the suitability for time-saving machine harvesting, a predominant request from growers. Uniform, high-quality broccoli crowns were identified as one of the key prerequisites to serve end-consumers' needs for healthy and nutritious food.
- **Promote Participatory and Sustainable Development:** Farmers were actively engaged during the innovation process, providing insights that resulted in innovation adoption. Higher broccoli stalks with few large leaves were identified to also better serve the conversion into organic fertilizer or animal feed in addition to enabling harvest efficiency and labor reduction.
- **Leverage Intermediaries and Provide Training:** Seminis® collaborated with cooperatives and harvest machine providers to maximize farmer outreach. Jointly, they trained farmers on the effective growing and harvesting of high-stalk broccoli to help ensure optimized farmer adoption.
- **Demonstrate ROI and Build Trust:** Seminis® communicated the ROI clearly to stakeholders in the R&D and trial process, showing High Rise's uniform maturity, yield potential, and consistent product quality have the ability to help growers achieve more efficient harvests.
- **Foster Knowledge Exchange and Evaluate Impact:** Seminis® enabled peer learning through farmer networks and tracked the impact of "High-Rise broccoli" on farm operations. Farmers growing High Rise have the ability to improve productivity through efficient harvests and less harvest passes.

Throughout the whole innovation process Bayer kept continuous exchange with stakeholders via networking events such as the annual Seminis Idea Exchange (IX) Field Days. The information gathered via such platforms ensures that testimonials from growers, shippers, machine providers, etc. are constantly screened for improvement opportunities in the development process to align consumer needs with farmer needs and other stakeholder benefits in the crop value chain for shared benefits.

The High Rise example showcases how innovation has a high probability of success by building partner networks from early development stages and leveraging on the impact assessment of innovations. Although only a small proportion of broccoli farmers apply machine-harvesting to date, more work among industry partners to drive adoption rates needs to be done, e.g. including "public-private" partnerships in the emerging countries. Nevertheless, this example demonstrates how innovative breeding solutions at the crossroads of former innovation frameworks can help improve people's lives, address one of the industry's biggest pain points, labor shortage, and support sustainability for the future [48-50].

Conclusion and Recommendations: From Concept to Practice

The adoption of agricultural innovations, including digital technologies and broader agritech solutions, requires a comprehensive, multifaceted approach addressing complex and unique technological, regulatory, and socio-economic challenges. Despite their potential benefits, low adoption rates among farmers often stem from unclear returns on investment (ROI), high costs, and the alignment of new technologies with existing practices rather than resistance to change. To facilitate meaningful transformation, stakeholders must streamline regulatory processes through mechanisms like "regulatory sandboxes," while governments should implement adaptive policies that foster open innovation ecosystems and incentivize sustainable practices through targeted subsidies and tax benefits. Establishing robust "public-private" collaborations, enhancing rural digital infrastructure, and investing in education and training programs are critical to equipping farmers with the tools to adopt transformative technologies. Supporting small-scale, localized agricultural trials tailored to specific regional conditions can generate breakthrough innovations with possibly broader applicability. Risk mitigation strategies, such as specialized insurance schemes and collaborative risk-sharing models, will provide farmers with the confidence to experiment with new approaches. By promoting participatory development that involves farmers in technology design, integrating clear sustainability objectives, demonstrating potential ROI, fostering knowledge exchange, and aligning regulatory frameworks with agricultural innovation policies, the agricultural sector can potentially create a more resilient, adaptive, and sustainable food system. By addressing these interconnected challenges, stakeholders can drive greater adoption of agricultural innovations, ultimately leading to improved productivity, sustainability, and resilience within the agriculture sector.

Conflict of Interest

This research was funded by Bayer Crop Science through a project with students from Harvard Undergraduate Consulting on Business and the Environment and ELFIN Consulting, which provided insights on transformative innovation in agriculture.

Author Contributions

VK: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing
RM: Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing
DB: Writing – original draft, Writing – review & editing
CS: Writing – original draft, Writing – review & editing

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