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Technology-Driven Resilience in Horticulture: A Comparative Critical Review of Kiwifruit and Apple Systems in New Zealand

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***Abstract*— *New Zealand's horticulture sector represents a globally recognized model of innovation-driven resilience, particularly within kiwifruit and apple production systems. This study employs a review-cum-analytical approach to evaluate the role of technological interventions in enhancing resilience under both biotic and abiotic stresses. The Kiwifruit system demonstrates transformative resilience following the outbreak of Pseudomonas syringae pv. actinidiae (Psa), driven by rapid varietal innovation, strengthened biosecurity frameworks, and centralized governance. In contrast, Apple systems exhibit adaptive resilience, characterized by incremental technological advancements in precision agriculture, automation, and data-driven orchard management. The findings highlight that resilience is an emergent property arising from the dynamic integration of biological, technological, and institutional systems.*

***Keywords*— Apple systems, Climate adaptation, Digital agriculture, Horticulture resilience, Kiwifruit, Robotics**

I. INTRODUCTION

Horticultural systems are increasingly vulnerable to climate change, emerging pests and diseases, labor shortages, and market volatility (FAO, 2017; FAO, 2022; IPCC, 2014; IPCC, 2023). These challenges necessitate the development of resilient agricultural systems capable of sustaining productivity under uncertainty (Foley et al., 2011; Pretty et al., 2010).

Resilience is defined as the capacity of systems to absorb disturbances, adapt, and transform in response to change (Holling, 1973; Folke et al., 2010). Advances in digital agriculture, genomics, and precision farming have significantly enhanced resilience potential (Gebbers and Adamchuk, 2010; Klerkx et al., 2019; Zhang et al., 2024).

New Zealand provides a globally relevant case due to its export-oriented horticulture systems, particularly kiwifruit (*Actinidia spp.*) and apple (*Malus domestica*) (Hall and McPherson, 2013; Plant & Food Research, 2021). These systems exhibit contrasting resilience pathways shaped by technological and institutional factors.

Despite operating under similar agro-climatic conditions, these systems exhibit distinct technological trajectories and resilience strategies. This paper aims to:

1. Analyze technological innovations in kiwifruit and apple systems
2. Compare resilience pathways under biotic and abiotic stresses
3. Identify transferable lessons for global horticulture

II. MATERIALS AND METHODS

A systematic review-cum-comparative analytical approach was employed to study, integrating literature from 2005–2026. The inclusion criteria were applied for data collection from Peer-reviewed articles (2005–2026), High-impact journals (Scopus, Web of Science, ScienceDirect, SpringerLink) focusing on horticulture, resilience, digital agriculture, robotics. A comparative framework was developed based on: Technological innovations; Biological resilience mechanisms and Institutional structures. The Resilience pathways were categorized as Transformative resilience and Adaptive resilience.

III. RESULTS

The comparative analysis reveals that both kiwifruit and apple production systems in New Zealand are increasingly characterized by technology-enabled intensification, although the scale, drivers, and modes of integration differ significantly. Across both systems, resilience is underpinned by three interrelated technological domains: digital and precision agriculture, automation and robotics, and genomics-driven innovation.

3.1 Technological Drivers of Resilience Across Systems

The comparative synthesis reveals that both kiwifruit and apple production systems in New Zealand are increasingly dependent on technology-enabled intensification, although the nature and depth of integration differ significantly. Across both systems, three dominant technological domains were identified: Digital and Precision Agriculture which is the integration of sensor-based monitoring systems, remote sensing, and AI-driven analytics has enabled real-time decision-making at the orchard level. Precision irrigation, fertigation, and canopy management have resulted in: Improved water-use efficiency; Reduced nutrient losses and Enhanced yield predictability. These findings align with recent studies demonstrating that precision horticulture significantly improves resource-use efficiency and sustainability (Zhang et al., 2024; Shamshiri et al., 2024).

Automation technologies have been widely adopted to address labor shortages and improve operational efficiency. Key applications include Robotic harvesting and thinning, Automated grading and sorting systems and AI-based fruit detection and yield estimation. The apple system shows a higher degree of labor-replacement automation, whereas kiwifruit systems emphasize process optimization technologies, particularly in pollination and postharvest handling (Bac et al., 2014; Bac et al., 2023; Bell, 2025; He et al., 2022; Karkee et al., 2022).

Advances in genomic selection, marker-assisted breeding, and genome editing have significantly contributed to resilience by improving Disease resistance, Climate adaptability and Fruit quality traits. The kiwifruit industry, in particular, has benefited from rapid cultivar innovation following disease outbreaks, highlighting the importance of genetic resilience (Faiz et al., 2026; Crossa et al., 2023; Nadarajan et al., 2023).

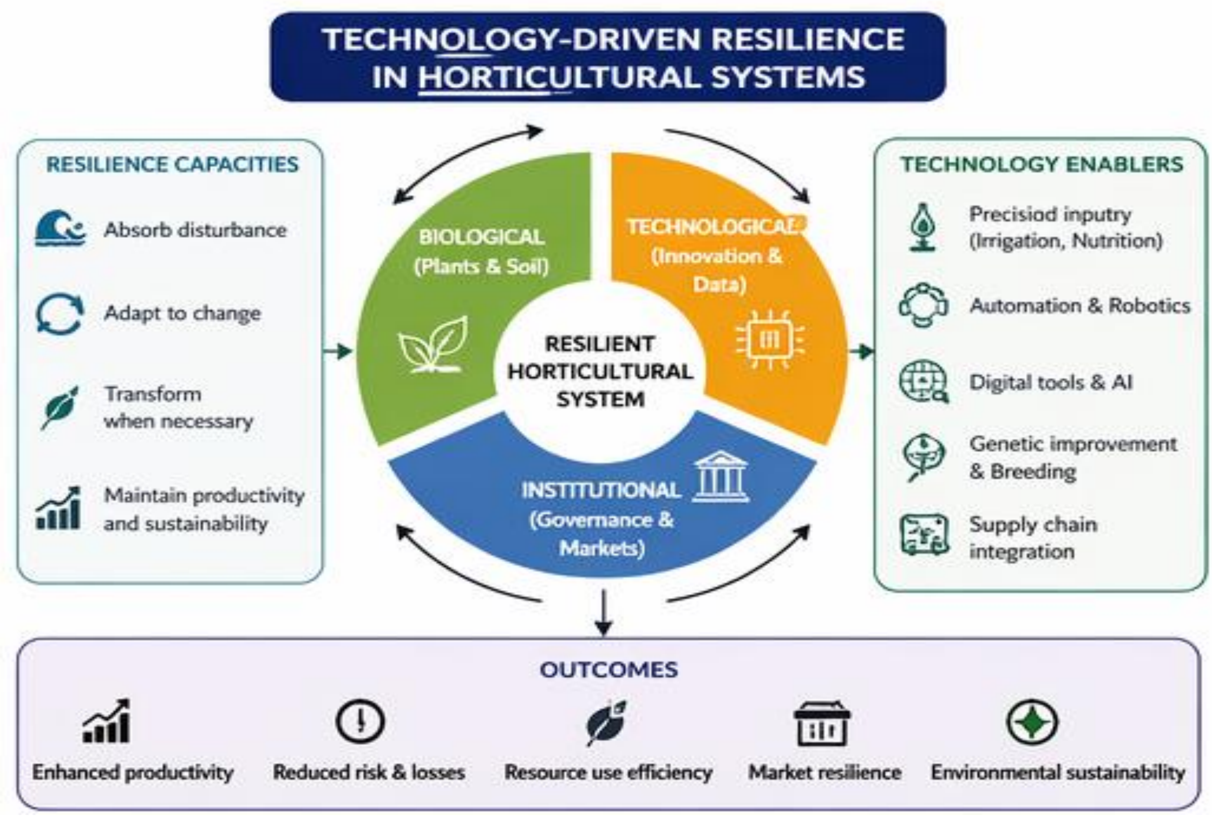

Fig.1: Conceptual framework of technology-driven resilience in horticultural systems.

3

.2 Kiwifruit System: Evidence of Transformative Resilience

The kiwifruit system provides a clear example of transformative resilience, where a major disruption led to systemic restructuring.

The outbreak of *Pseudomonas syringae pv. actinidiae* (Psa) caused severe economic losses and threatened the viability of the industry. However, the response involved the rapid development and commercialization of resistant cultivars (e.g., SunGold); strengthening of biosecurity and surveillance systems and integration of advanced technologies across production and supply chains. This crisis-driven innovation resulted in a more robust and technologically advanced system compared to the pre-outbreak phase (Greer and Saunders,2012; Manktelow et al., 2018; Smith et al., 2024).

The transformation extended beyond biological adaptation to include: Institutional restructuring and centralized coordination; Enhanced research–industry collaboration and Standardization of production practices. This reflects a shift from reactive management to proactive resilience-building, consistent with theoretical models of transformative adaptation (Manktelow et al, 2028, 2023; Folke et al., 2010)

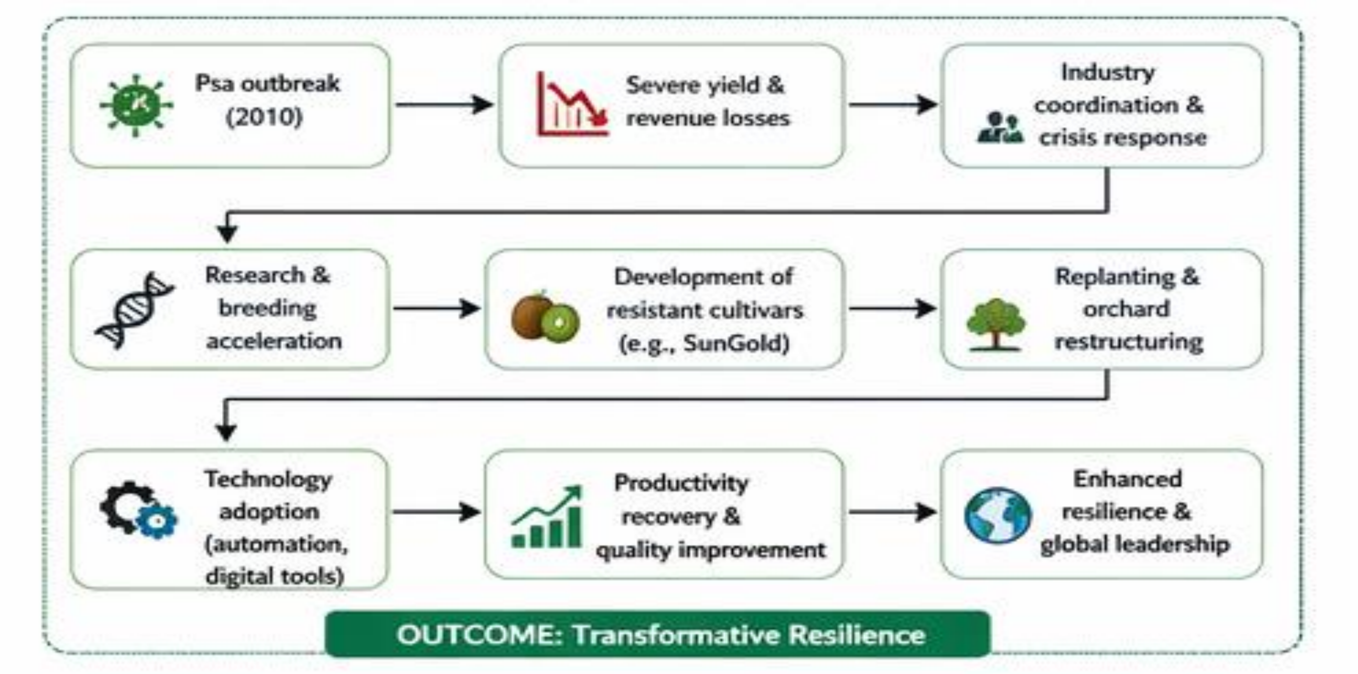

Fig.2: Flowchart of transformative resilience in the Kiwifruit industry.

3.3 Apple System: Evidence of Adaptive Resilience

In contrast, the apple system demonstrates adaptive resilience, characterized by gradual and continuous improvements.

The apple sector has progressively integrated technologies such as: High-density orchard systems; Precision nutrient and irrigation management; Robotics for labor-intensive operations Jamshidi et al., 2025; Karkee et al., 2022). These innovations have improved productivity while maintaining system stability (Duckett et al., 2022; Tustin et al., 2022).

Labor shortages have been a primary driver of technological adoption in apple systems, leading to Increased reliance on automation and Development of labor-efficient orchard architectures. Similarly, climate variability has prompted the adoption of Protective netting systems and Climate-resilient cultivars. These changes reflect incremental adaptation rather than systemic transformation (Ananthakrishnan et al., 2025; Saxton et al., 2022).

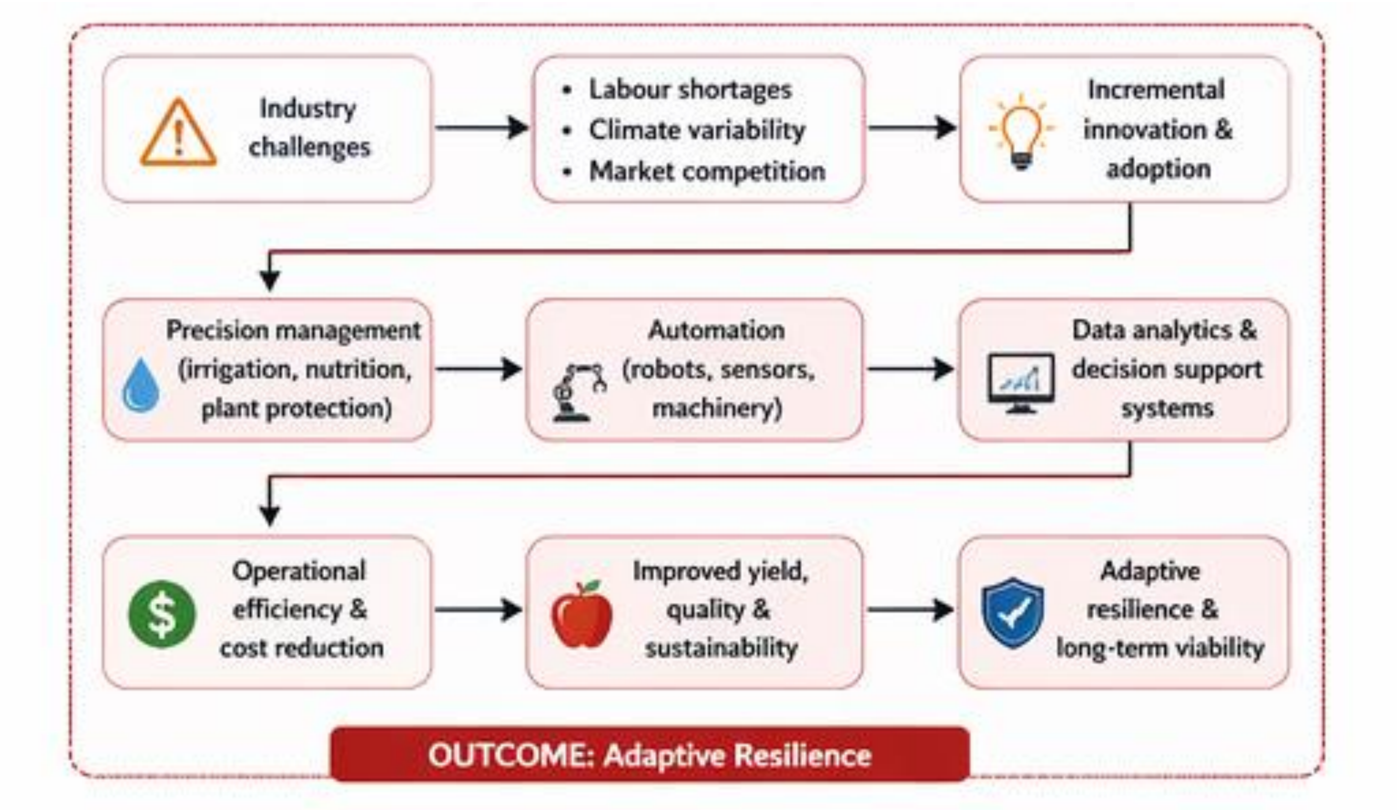

Fig.3: Flowchart of adaptive resilience in the Apple industry.

3.4 Comparative Synthesis of Resilience Pathways

The table 1 tabulates the comparative analysis of different parameters among Kiwifruit system and Apple system. The examination reveals fundamental differences among the two systems. The Kiwifruit system is crisis-driven, institutionally coordinated and transformation-oriented while the Apple system is efficiency-driven, decentralized, adaptation-oriented. However, both systems converge in Increasing digitalization; Integration of automation technologies and Emphasis on sustainability and climate resilience.

Table 1: Comparative Analysis of different parameters among Kiwifruit system and Apple system

Parameter	Kiwifruit System	Apple System
Resilience Type	Transformative	Adaptive
Governance	Centralized	Decentralized
Innovation Driver	Crisis response	Efficiency & sustainability
Key Technologies	Breeding, Robotics	Precision agriculture, AI
Major Stressors	Disease	Labor, climate variability

DIMENSION	KIWIFRUIT SYSTEM	COMPARISON	APPLE SYSTEM
Disease management & bioscurity	• Psa-V induced industry-wide transformation • Resistant cultivars (e.g., 'SunGold', 'Zespri Gold3') • National biosecurity surveillance & risk modelling	⟷	• Focus on pests (e.g., codling moth, aphids) & diseases (e.g., scab, fire blight) • Integrated pest management (IPM) • Targeted biosecurity protocols
Genetic improvement	• Marker-assisted breeding • Rapid cultivar replacement post-Psa • Long-term breeding pipeline	⟷	• Conventional & genomic-assisted breeding • Emphasis on quality, storability, colour • Climate-resilient cultivar development
Precision & digital tools	• Orchard sensors & microclimate monitoring • Variable rate irrigation & fertigation • Yield prediction & canopy analytics	⟷	• Extensive use of sensors, IoT, remote sensing • Decision support systems (DSS) • AI-based yield estimation & fruit sizing
Automation & mechanization	• Robotic pollination & harvesting (emerging) • Automated grading & packing lines • Electric vehicles & smart machinery	⟷	• Robotic thinning, harvesting (pilot scale) • Autonomous orchard platforms • Labour-saving tools
Climate adaptation strategies	• Frost protection (fans, sprinklers, wind machines) • Irrigation management & drainage systems • Climate modelling & risk mapping	⟷	• Protective netting & hail systems • High-density planting & canopy management • Irrigation scheduling & heat stress mitigation
Supply chain & market integration	• Centralized supply chain (Zespri model) • Traceability & digital market intelligence • Strong brand & consumer engagement	⟷	• Multiple packhouses & exporters • Traceability systems (e.g., NZGAP) • Market diversification

Fig.4: Comprehensive comparison of technological dimensions between Kiwifruit and Apple systems.

IV. DISCUSSION

The findings confirm that technology is a critical enabler of resilience in modern horticulture. The integration of AI, robotics, and genomics has transformed traditional production systems into data-driven, adaptive systems. The digital agriculture enables: Predictive decision-making; Risk minimization and Resource optimization. These capabilities are essential under increasing climate variability and market uncertainty (Klerkx et al., 2022; Wolfert et al., 2017).

The study highlights two distinct resilience pathways: Transformative Resilience (Kiwifruit) which is triggered by major disruption (Psa outbreak), leads to systemic reorganization and involves institutional, technological, and biological changes. The Adaptive Resilience pathway (Apple) that is driven by gradual pressures (labor, climate), Focuses on incremental improvements and maintains existing system structure. This distinction aligns with resilience theory, which emphasizes the role of disturbance in triggering transformation (Folke et al., 2010; Walker et al., 2004).

A key insight from this study is the importance of institutional coordination in shaping resilience outcomes. The kiwifruit industry benefits from centralized governance, enabling rapid and coordinated responses and the apple industry operates under a decentralized structure, resulting in slower but flexible adaptation. This suggests that governance structures can either accelerate or constrain technological adoption and resilience building (Klerkx et al., 2019).

Technology-driven resilience contributes to sustainability through reduced input use (water, fertilizers); lower environmental impact and by improved resource efficiency. However, concerns remain regarding: Energy use in high-tech systems; Environmental costs of mechanization and Long-term sustainability of intensive production. These trade-offs highlight the need for balanced and context-specific technological integration (Rockström et al., 2017; Rockström et al., 2023).

Despite technological advancements, several challenges persist such as -High capital investment requirements; Limited access for small-scale growers and Skill gaps in adopting advanced technologies. These factors may exacerbate inequalities within the horticulture sector, particularly in developing countries (FAO, 2022).

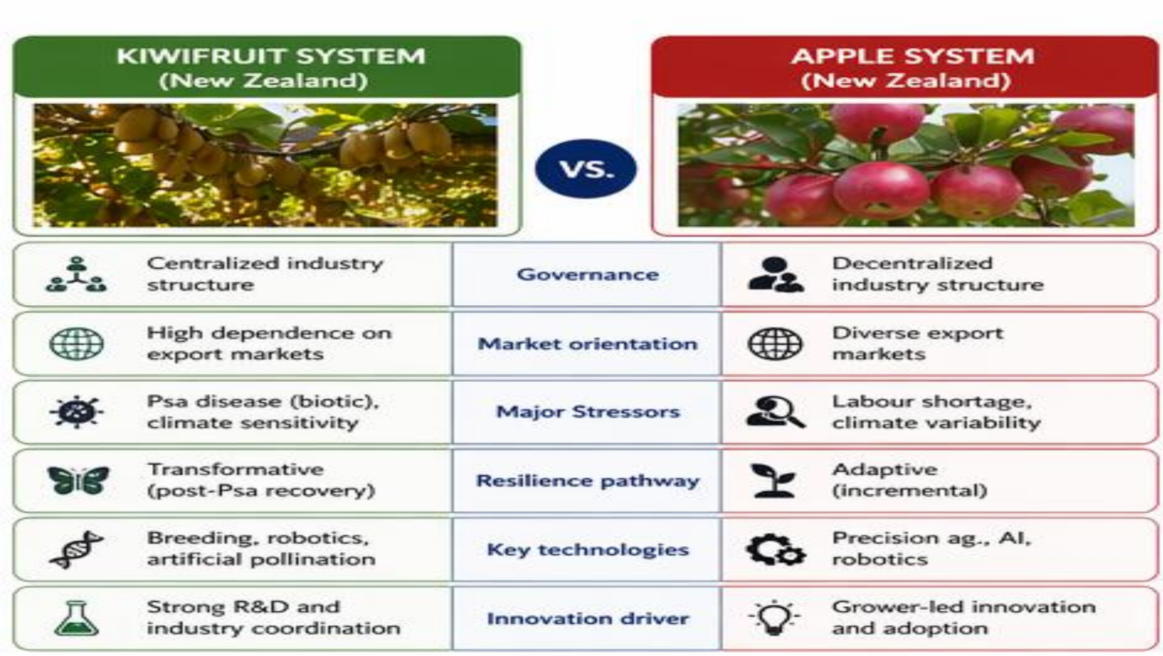

Fig.5: Comparative overview of Kiwifruit and Apple systems in New Zealand

The next phase of resilience in horticulture will be driven by Digital twins for real-time system simulation; Genome editing (CRISPR) for multi-stress resistance; AI-enabled autonomous orchards and the Blockchain-based traceability systems. These technologies have the potential to create fully integrated, intelligent horticultural systems capable of responding dynamically to environmental and market changes (Folke et al., 2023; Gao, 2023; Pedersen et al, 2023; Smith et al., 2025).

The New Zealand case provides transferable lessons: Crisis can catalyze innovation and transformation; Incremental adaptation remains essential for long-term stability and Integration of technology, governance, and biology is critical. These insights are particularly relevant for developing countries aiming to build climate-resilient horticultural systems.

The findings underscore that technology is not merely an enabling tool but a central structural component of modern horticultural resilience**.** The convergence of artificial intelligence, robotics, and genomics is transforming traditional orchard systems into adaptive, data-driven socio-ecological systems capable of responding dynamically to environmental and economic uncertainties (Klerkx et al., 2022; Wolfert et al., 2017). However, the effectiveness of these technologies is strongly mediated by institutional arrangements, highlighting the co-evolution of technological and governance systems.

V. CONCLUSION AND FUTURE PROSPECTS

This study provides a comparative analysis of technology-driven resilience in kiwifruit and apple production systems in New Zealand, demonstrating that resilience in horticulture emerges from the interaction of technological innovation, ecological processes, and institutional frameworks rather than from isolated interventions. The kiwifruit system illustrates transformative resilience, where the outbreak of *Pseudomonas syringae* pv. *actinidiae* (Psa) triggered rapid cultivar innovation, strengthened biosecurity systems, and coordinated institutional responses, resulting in a more robust and restructured production system. In contrast, the apple system reflects adaptive resilience, achieved through incremental adoption of precision agriculture, automation, and improved orchard management practices in response to ongoing challenges such as labor shortages and climate variability.

The coexistence of these distinct resilience pathways highlights the importance of pathway diversity in enhancing overall sectoral stability. While transformative approaches enable rapid recovery and system renewal following major shocks, adaptive strategies ensure sustained productivity under continuous stress conditions. Across both systems, digital agriculture technologies—including artificial intelligence, robotics, and data-driven decision tools—play a central role in improving efficiency, optimizing resource use, and reducing vulnerability to environmental and economic uncertainties. However, the benefits of these technologies depend on supportive institutional environments, access to skilled labor, and equitable dissemination of innovations.

Despite significant progress, challenges remain, including high capital costs, technological complexity, and unequal access, particularly for smaller producers. Additionally, concerns regarding the environmental footprint of technologically intensive systems underscore the need for balanced approaches that align productivity gains with sustainability objectives. Looking ahead, the integration of advanced technologies such as digital twins, genome editing, and autonomous orchard systems is expected to further enhance resilience, alongside the adoption of climate-smart practices and strengthened biosecurity frameworks. Ensuring inclusive access to these innovations, supported by effective policy and institutional mechanisms, will be critical for scaling resilience.

Overall, the findings emphasize that technology-driven resilience is multidimensional and context-dependent, requiring integrated strategies that combine technological, ecological, and institutional dimensions. The New Zealand case offers transferable insights for global horticulture, demonstrating that resilience can be leveraged not only to withstand disruptions but also to drive innovation and long-term sustainability.

POLICY RECOMMENDATIONS

The policy recommendations for enhancing technology-driven resilience in horticulture-

- **Promote Integrated Innovation Systems:** Strengthen collaboration between research institutions, industry stakeholders, and policymakers to accelerate technology adoption and knowledge transfer.
- **Support Inclusive Technology Access:** Develop subsidies, financing mechanisms, and low-cost innovations to ensure accessibility for smallholder and resource-limited growers.
- **Invest in Capacity Building:** Enhance technical training programs to address skill gaps in digital agriculture, robotics, and data-driven decision-making.
- **Strengthen Biosecurity Frameworks:** Implement proactive surveillance systems, early warning mechanisms, and rapid response strategies for emerging pests and diseases.
- **Encourage Climate-Smart Practices:** Incentivize precision irrigation, renewable energy use, and sustainable intensification to reduce environmental impacts.
- **Foster Data Infrastructure and Digital Platforms:** Develop standardized data-sharing systems and digital tools to support real-time decision-making and predictive analytics.
- **Enable Supportive Policy Environments:** Provide funding for innovation, establish regulatory frameworks for emerging technologies (e.g., genome editing), and promote sustainable production standards.
- **Facilitate Global Knowledge Transfer:** Adapt successful models (e.g., New Zealand systems) to regional contexts through international collaboration and policy exchange.

VI. DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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