

Operational Risk Integration for Regulatory-Driven Export Sustainability: An Operations Management Study of the South African Citrus Supply Chain

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Abstract

Global agri-food export supply chains operating under stringent regulatory regimes face increasing operational and compliance risks that directly affect market continuity. From an Industrial Engineering and Operations Management perspective, this paper examines how the integration of operational, quality, and regulatory risk controls supports export sustainability in highly regulated markets. Using empirical survey data from stakeholders in the Western Cape Province, South Africa within the citrus export supply chain, the study evaluates current risk integration practices and their perceived impact on compliance performance and operational stability. Descriptive statistical analysis indicates that organisations adopting system-integrated risk management—rather than fragmented compliance approaches—demonstrate stronger resilience against regulatory disruptions and improved preparedness for evolving export requirements. The findings contribute to IEOM scholarship by positioning integrated risk management as a core operational capability for sustainable participation in global value chains.

Keywords

Integrated Risk Management, Export Sustainability, Operations Management, Regulatory Compliance, Agri-Food Supply Chains

1. Introduction

International export-oriented supply chains are increasingly shaped by regulatory complexity, sustainability expectations, and heightened operational risk exposure (Phologane et al. 2024). The proliferation of Sanitary and Phytosanitary (SPS) measures and private food safety standards has transformed compliance from a passive administrative function into a strategic operational determinant, particularly for agri-food exporters supplying highly regulated markets (Xue et al. 2025). For these exporters, operational failures linked to risk misalignment—such as phytosanitary non-compliance, documentation errors, or inconsistent application of control measures—can trigger shipment rejections, cost escalation, and long-term market exclusion (Bandaly et al. 2012; NAQS 2019). Indeed, non-compliance with stringent phytosanitary import regulations may result not only in the destruction of rejected consignments but also in the suspension of entire export programmes, with cascading economic repercussions for producer economies (Phologane et al. 2024). The European Union (EU) represents a particularly regulatory-intensive destination, where compliance is embedded within operational decision-making rather than treated as a peripheral function (European Commission 2022). Recent enforcement actions demonstrate this trajectory: the EU's implementation of mandatory cold treatment requirements for South African citrus to manage False Codling Moth (FCM) risks—introduced mid-season in 2022—resulted in major port disruptions, blocked consignments, and significant compliance cost burdens (CGA 2023; European Commission 2025). These regulations operate within a "zero-tolerance" framework for regulated pests, where the detection of a single live FCM constitutes grounds for shipment rejection and potential disqualification of production sites from export eligibility (CRI 2025). Such stringent phytosanitary regimes necessitate that compliance be integrated into orchard management, post-harvest processing, and cold chain logistics—requiring systematic operational coordination rather than retrospective administrative verification.

South Africa's citrus export sector provides an instructive case for examining how operational risk integration influences export sustainability under regulatory pressure. As the world's second-largest citrus exporter, with the EU serving as its primary market destination, the sector faces heightened exposure to regulatory shocks while maintaining sophisticated quality management infrastructures (CGA 2023). The industry's recent experience with FCM management systems, Citrus Black Spot (CBS) protocols, and evolving cold treatment requirements illustrates the operational challenges of integrating regulatory compliance into existing quality management frameworks (Phologane et al. 2024). This paper therefore investigates the role of integrated risk management systems in supporting sustained export performance, with specific emphasis on operational coordination, compliance reliability, and system-level resilience. Specifically, it examines how the integration of phytosanitary risk controls with operational quality management systems affects the sector's capacity to maintain market access under conditions of regulatory stringency.

2. Literature Review

Recent literature highlights that supply chain risk management (SCRM) has matured into a strategic capability essential for operational performance and continuity, especially in complex, globalised systems. In this evolving context, SCRM is no longer a back-office compliance activity but a core operational function that enables firms to anticipate, model, and mitigate disruptions across extended value chains. Recent reviews argue that despite advances, holistic and integrated SCRM approaches that cover all phases of risks (identification, evaluation, mitigation, monitoring) are still limited in practice (Das and Perona 2025).

2.1 Operational Risk in Export-Oriented Supply Chains

Operations management literature defines operational risk as the exposure of processes to disruptions arising from variability, uncertainty, and control failures (Slack et al. 2022). In export-oriented supply chains, operational risk is amplified by long lead times, coordination across organisational boundaries, and dependency on regulatory approval at multiple control points (Tang 2006). Studies in supply chain risk management emphasise that agricultural and food export chains are particularly vulnerable due to biological risks, seasonality, and perishability (Aqlan and Lam 2016). From an industrial engineering perspective, unmanaged operational risk manifests as process instability, rework, waste, and service failure. Christopher and Peck (2004) argue that resilience in such supply chains is primarily a function of process integration and information visibility rather than isolated risk mitigation actions. Academic work underscores that supply chain integration — the alignment of processes, information, and cross-functional coordination — improves risk management effectiveness and operational performance. For example, Munir et al. (2020) connect integrated risk management with enhanced operational outcomes, where better information flow and coordination reduce uncertainty and disruptions. Similarly, empirical research shows that strategic risk management

practices, when embedded operationally, lead to improved performance outcomes by reducing the negative effects of supply chain disruptions on decision-making and competitiveness (Singh and Hong 2020).

2.2 Risk Integration and Export Sustainability

Sustainability in export operations is increasingly linked to the stability and reliability of operational systems. Pagell and Wu (2009) argue that sustainable supply chains are characterised by proactive risk management and adaptive operational capabilities. Rather than treating sustainability as an external objective, operations-focused studies position it as an outcome of well-designed and controlled processes. Within agri-food supply chains, risk integration supports sustainability by reducing product losses, minimising compliance-related waste, and maintaining long-term market participation (Beske et al. 2014). This perspective supports the views of sustainability as inseparable from operational excellence and system performance.

2.3 Regulatory Compliance as Operational Capability

Regulatory compliance in international trade is increasingly viewed as an operational capability rather than a legal or administrative function. Studies highlight that compliance failures are often rooted in process misalignment, insufficient control integration, and limited system visibility (Munir et al. 2020; Jean 2024). Recent systematic reviews of supply chain sustainability risk management emphasise how firms are required to embed compliance with due diligence regulations into operational risk frameworks. The literature reports that traditional compliance-centric approaches often fail to account for broader stakeholder impacts or long-term resilience, reinforcing the need for integrated operational risk systems aligned with regulatory regimes (Both and Wilhelm 2025).

2.4 Agri-Food Supply Chain Risks and Mitigation

In the agri-food sector, recent literature recognises the unique risk profile these supply chains face — including economic, environmental, and regulatory vulnerabilities. A comprehensive review in *Frontiers in Sustainable Food Systems* identifies economic and regulatory risks as significant disruptors in agri-food systems, reinforcing the need for multi-layered mitigation strategies that extend beyond production into distribution and export compliance (Xue et al. 2025). This work highlights that sudden regulatory changes or border controls can significantly disrupt trade flows and product continuity, underscoring the relevance of operational risk integration in export-oriented agri-food contexts.

2.5 Technology, Integration and Future Directions

Emerging research also points to the role of digital technologies and analytics in driving advanced risk integration. Studies on analytics-driven supply chain visibility and AI-enabled risk assessment suggest that predictive analytics and machine learning can significantly improve proactive risk detection and mitigation — an important consideration for future operational systems in highly regulated supply chains (Zheng and Brintrup 2025).

3. Methods

A quantitative, descriptive research design was adopted using a structured survey questionnaire. The instrument targeted stakeholders directly involved in citrus export operations and risk management activities. Table 1 summarises the research design and methodological approach adopted in this study. It outlines the quantitative, cross-sectional survey design, identifies the unit of analysis and target respondents within the export-oriented citrus supply chain, and specifies the data collection, measurement scales, and analytical techniques employed. The table highlights the study's focus on examining operational risk integration and regulatory compliance using descriptive statistical analysis.

Table 1. Research design and methodological overview

Aspect	Description
Research approach	Quantitative, descriptive survey
Research design	Cross-sectional
Unit of analysis	Export-oriented citrus supply chain organisations
Target respondents	Farm owners, operations managers, quality/compliance managers
Data collection method	Structured questionnaire
Measurement scale	Nominal and ordinal (Likert-type)

Aspect	Description
Data analysis technique	Descriptive statistics (frequency and percentage analysis)
Analytical focus	Operational risk integration and regulatory compliance

Figure 1 illustrates a sequential research framework that highlights the analytical focus of the study. It shows a stepwise relationship where Operational Processes form the foundation, feeding into Integrated Risk Controls, which in turn support Compliance Reliability, ultimately contributing to Export Sustainability. The diagram suggests a logical flow where improvements or interventions at each stage positively influence the subsequent stage, emphasizing the interconnectedness of operational efficiency, risk management, regulatory compliance, and sustainable export outcomes.



Figure 1. Research Framework and Analytical Focus

Primary data were collected through a survey distributed across the Western Cape Province citrus value chain, including farm owners, managers, quality assurance personnel, and compliance specialists. A total of 121 valid responses were analysed (Table 2).

Table 2. Frequency of respondent

Respondent Role	Frequency	Percentage (%)
Farm owners	59	48.8
Operations managers	31	25.6
Quality / compliance managers	22	18.2
Other operational roles	9	7.4
Total	121	100

4. Results and Discussion

The analysis of 121 valid responses reveals a supply chain sector where risk management has transitioned from compliance auditing to operational system integration, yet significant structural challenges persist across all producer scales. Descriptive statistics indicate that while operational-level integration is mature (Mean = 4.16, SD = 0.68 on a 5-point scale), strategic coordination and resource constraints reveal vulnerability gaps that threaten long-term export sustainability.

4.1 Respondent and Organisational Profile

The sample reflects senior operational decision-making authority, with 48.8% (n=59) identifying as farm owners and 25.6% (n=31) as farm managers, indicating that responses capture strategic-level perspectives. Production managers (11.6%) and quality/compliance specialists (6.6%) comprise the remainder, confirming that risk management responsibility is embedded within line operations rather than isolated legal departments. Organisational scale analysis reveals a balanced distribution across producer categories: small-scale (R50,000–R5 million turnover, 39.5%),

medium-scale (R5 million–R20 million, 40.3%), and large-scale (above R20 million, 20.2%). Notably, experience levels are substantial, with 67.8% of producers having 15 or more years in fresh produce farming, and 49.6% exporting to the EU for 15+ years. This suggests a mature industry cohort with deep institutional knowledge, yet potentially encumbered by legacy operational architectures. Certification patterns reveal GlobalG.A.P as the universal baseline (100% of valid respondents), while secondary certifications show selective adoption: SIZA (6.3%), Tesco Nurture (23.9%), Albert Heijn PPP (12.7%), and BRC (5.4%). This stratification indicates a tiered compliance architecture where GlobalG.A.P serves as the operational foundation, with retailer-specific protocols layering additional requirements atop integrated management systems. Packhouse logistics data expose structural fragmentation: only 24.8% of producers own their packhouse facilities, while 52.1% utilize third-party packhouses via fee-for-service arrangements, and 23.1% use cooperative member-owned facilities. This fragmentation creates inherent coordination risks, as 76.9% of producers depend on external entities for critical control points in the export chain.

4.2 Risk Management Architecture and Implementation Approaches

Organisations demonstrate divergent strategies for Food Safety Management System (FMS) integration. Nearly half (49.2%, n=59) rely on external consultants or third parties for implementation, while 33.3% (n=40) utilize farm-owner-led integration, and only 16.7% (n=20) employ dedicated internal personnel. This heavy reliance on external expertise (82.5% combined external/owner-led vs. 16.7% internal capacity building) suggests potential fragility in institutional knowledge retention and continuous improvement capabilities.

4.3 Operational Integration of Compliance Controls

Empirical evidence strongly supports the operational embedding of risk controls. As illustrated in Figure 2, 91.4% of respondents (n=93) report that implementation occurs at the operational level (integrated records, work instructions, and checklists), while 83.9% confirm strategic-level policy integration. Internal audit systems demonstrate high maturity: 82.8% conduct regular farm-level audits, and 74.2% utilize integrated audits reviewing multiple stakeholder requirements (GlobalG.A.P, FMS, etc.) simultaneously.

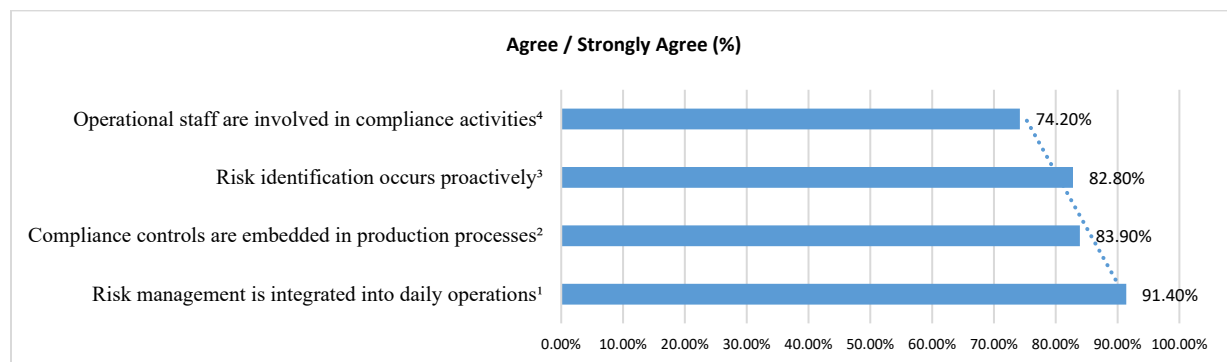


Figure 2. Integration of Risk Management into Operational Processes

4.4 Compliance Risk Profile and Non-Compliance Patterns

Analysis of perceived non-compliance risks reveals a biological-dominant threat landscape (Figure 3). Phytosanitary non-compliance—specifically the detection of regulated pests (false codling moth)—ranks as the predominant concern, with 58.8% of respondents (n=57/97) acknowledging this as a significant risk (Mean = 3.49, SD = 1.23, where 5 = Strongly Agree). This aligns with the high-stakes regulatory environment of EU phytosanitary controls. Chemical compliance constitutes the secondary risk tier: 45.4% cite exceeding pesticide Maximum Residue Limits (MRLs) as critical (Mean = 3.05, SD = 1.24). Documentation errors—specifically phytosanitary certificate issues—rank lower (32.0%), followed by labelling non-compliance (30.9%).

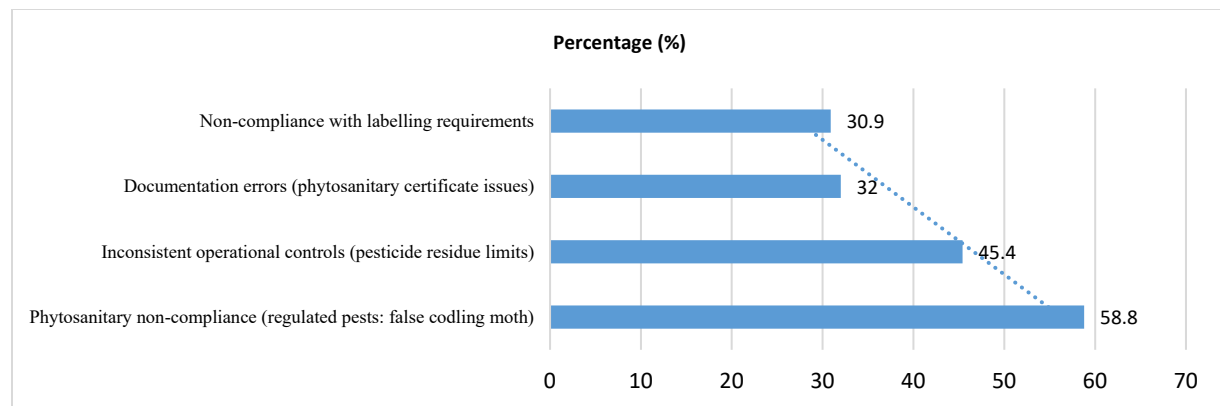


Figure 3. Key Risk Areas Affecting Export Compliance

Factor analysis of non-compliance items (KMO = 0.821; Bartlett's test $p < 0.001$) extracts a single component explaining 68.7% of variance (Cronbach's $\alpha = 0.921$), suggesting that exporters perceive these risks as manifestations of a unified *system reliability* factor rather than isolated failures. All seven non-compliance variables load strongly on this factor (0.625–0.911), with documentation issues and phytosanitary certificates showing the highest communalities (0.830 and 0.822 respectively), underscoring their systemic interdependence.

4.5 Implementation Challenges: A Three-Factor Structure

Contrary to expectations that farm scale would determine implementation capacity, ANOVA results reveal no statistically significant differences between small, medium, and large-scale producers across operational, training, or financial challenge dimensions ($F = 1.984$, $p = 0.144$; $F = 1.107$, $p = 0.335$; $F = 0.613$, $p = 0.544$ respectively). This homogeneity suggests that regulatory complexity creates *sector-wide* systemic burdens regardless of organisational scale.

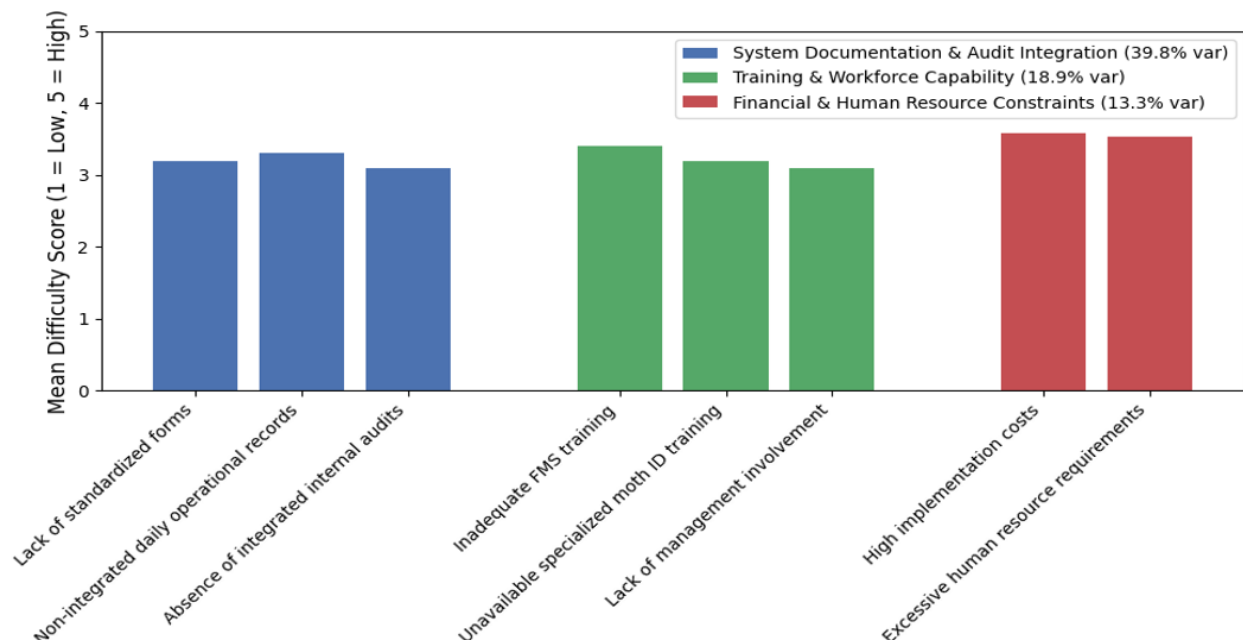


Figure 4. Implementation Challenges of FMS – Three-Factor Structure

Note: X-axis: Challenge Items (grouped by Factor); Y-axis: Mean Difficulty Score (1 = Low, 5 = High)

Exploratory factor analysis of implementation difficulties ($KMO = 0.715$) identifies three distinct challenge dimensions explaining 71.96% of total variance:

Factor 1: System Documentation and Audit Integration (39.8% variance; $\alpha = 0.831$)

- Lack of standardized forms
- Non-integrated daily operational records
- Absence of integrated internal audits
- *Interpretation:* Operational challenges centre on information system design and standardized work procedures—core industrial engineering domains.

Factor 2: Training and Workforce Capability (18.9% variance; $\alpha = 0.658$)

- Inadequate FMS training at all levels
- Unavailability of specific false codling moth identification training
- Lack of management involvement
- *Interpretation:* Human capital constraints, particularly specialized technical training for biological risk detection, constrain system effectiveness.

Factor 3: Financial and Human Resource Constraints (13.3% variance; $\alpha = 0.767$)

- High implementation costs (Mean = 3.59, highest difficulty score)
- Excessive human resource requirements (Mean = 3.54)
- *Interpretation:* Resource intensity represents a distinct ordinal constraint, with cost pressure exceeding procedural difficulties (Figure 4).

Notably, "lack of government support" generates polarized responses (Mean = 3.53, SD = 1.32), with 30.6% strongly agreeing it constitutes a barrier while 28.2% disagree, reflecting heterogeneous experiences with institutional support mechanisms.

5. Discussion: Risk Integration as Operational Capability

The empirical findings substantiate the reconceptualization of regulatory compliance from an administrative/legal function to an operational capability embedded within process architecture (Jean 2024; Both and Wilhelm 2025). The high adoption of operational-level integration (91.4%) alongside the universal GlobalG.A.P certification baseline suggests that South African citrus producers have structurally integrated compliance into production systems rather than treating it as a post-hoc verification activity.

From an Industrial Engineering perspective, this integration manifests as systems thinking in practice: the factor analysis revealing a unified non-compliance construct (68.7% variance) supports Christopher and Peck's (2004) argument that supply chain resilience emerges from process integration and information visibility rather than isolated risk mitigation. When exporters view phytosanitary pests, residue limits, and documentation errors as correlated manifestations of system reliability rather than independent hazards, they implicitly acknowledge the systemic nature of operational risk.

The dominance of biological risks (false codling moth) over administrative risks carries significant operational design implications. Unlike documentation errors (which lend themselves to poka-yoke and administrative controls), pest management requires dynamic process control embedded across orchard management, harvest timing, and post-harvest cold chain protocols. The 58.8% risk perception rate for phytosanitary compliance, coupled with the high cost of implementation (Mean = 3.59), suggests that sustainable export performance requires continuous investment in integrated pest management systems—a capital and knowledge-intensive operational capability.

The absence of scale effects in implementation challenges (ANOVA $p > 0.05$) challenges conventional assumptions that larger producers possess superior risk integration capacity. This finding implies that regulatory complexity creates minimum operational capability thresholds that all exporters must meet regardless of size, potentially raising barriers to entry and consolidating market participation among firms capable of bearing systemic compliance costs. For industrial engineering practice, this suggests that scalable, modular risk management system designs—rather than scale-dependent resource allocations—are necessary to maintain sector-wide export sustainability.

The three-factor difficulty structure reveals a process-design gap in current implementations. While Factor 2 (training) and Factor 3 (financial resources) represent traditional resource constraints, Factor 1 (documentation/audit integration) specifically indicates underdeveloped standardized work systems and information flows—core IE intervention domains. The high loading of "lack of standardized forms" (0.880) and "non-integrated daily records" (0.818) suggests that even mature operations lack the documentation standardization necessary for statistical process control and continuous improvement cycles.

Finally, the consultant dependency observed (49.2% reliance on external expertise) presents a paradox for operational capability building. While external expertise facilitates initial system implementation, the relatively low proportion of farms employing dedicated internal personnel (16.7%) may limit the *dynamic capabilities* necessary to adapt to regulatory evolution (Pagell and Wu 2009). This externalization of risk management intelligence contrasts with the operational embedding of execution, creating potential fragility in strategic adaptation capacity.

6. Implications for Industrial Engineering and Operations Management Practice

The findings yield specific implications for IEOM practitioners in agri-food systems:

1. Design for Regulatory Resilience: Process design must incorporate *regulatory shock absorption* as a primary function, not merely compliance as a constraint. The significant variance in strategic-level integration (SD = 0.83) suggests that current systems over-optimize for operational compliance while under-investing in adaptive policy architecture.
2. Standardized Information Systems: The documentation integration factor (Factor 1) identifies a critical intervention point. IE practitioners should develop modular, scalable documentation and audit management systems that reduce the cognitive and administrative load of multi-certification compliance (GlobalG.A.P + SIZA + retailer protocols).
3. Specialized Human Capital Development: The unavailability of specific false codling moth identification training (loading 0.836 on Factor 2) highlights the need for technical training programs embedded within operational roles rather than external certification courses. Job instruction training (JIT) methodologies adapted for biological risk detection could address this capability gap.
4. Scale-Appropriate Technology: Given the non-significant scale effects, technology solutions for risk integration must demonstrate economies of scope rather than scale—enabling small and medium producers to achieve integration efficiencies without massive infrastructure investments (e.g., shared digital audit platforms for the 52.1% using third-party packhouses).

For policymakers and industry bodies, the findings support the development of harmonized operational frameworks that align EU phytosanitary requirements with standardized industry protocols, reducing the current redundancy between multiple certification schemes (GlobalG.A.P, SIZA, retailer-specific standards) and thereby lowering the compliance cost burden (Mean = 3.59) that threatens sector sustainability.

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Biographies

Lucrecia Valentine is the Programme Coordinator in the Department of Industrial and Systems Engineering at the Cape Peninsula University of Technology (CPUT). She holds qualifications in Food Technology and Quality and obtained her PhD in Commerce and Administration from Cranefield College. With 11 years of experience across various sectors of the food industry, Dr Valentine has developed extensive expertise in quality control, quality assurance, and management. Her experience as a lead auditor for an accredited certification body further broadened her exposure to manufacturing processes beyond the food industry, including the motor manufacturing, clothing, and construction sectors. Her research interests focus on operational optimisation, quality management, and food safety, with a growing emphasis on postgraduate research supervision. She has successfully supervised four master's students and is currently supervising five additional master's candidates towards the completion of their theses. Dr Valentine is actively involved in the Academic Staff Quality Desk, which is responsible for monitoring and promoting quality academic engagement among students and staff. She is also committed to advancing awareness of quality service delivery through her participation in the annual Quality Day commemoration hosted by the City of Cape Town.

Bingwen Yan is the Head of the Department of Operations Management in the Faculty of Business and Management Sciences at the Cape Peninsula University of Technology (CPUT). He holds a Doctor of Technology in Mechanical Engineering and has played a pivotal role in advancing higher education through his extensive contributions to teaching, learning, and curriculum development. Prof. Yan's research expertise spans industrial engineering, engineering management, operations management, and public administration. Throughout his academic career, he has made significant contributions to postgraduate education, having successfully supervised eight doctoral candidates and more than 30 master's students, thereby fostering a strong culture of research excellence. His scholarly work is widely recognised, with numerous publications in ISI- and DHET-accredited journals, as well as presentations at reputable international conferences. In addition, Prof. Yan actively contributes to academic quality and research governance through his service on conference organising committees, his role as a peer reviewer for leading journals and conferences, and his work as an evaluator of NRF-funded research projects and grant applications. Prof. Yan is a registered member of the International Council on Systems Engineering (INCOSE) and remains committed to bridging

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