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HACCP AND ISO FRAMEWORKS FOR ENHANCING BIOSECURITY IN GLOBAL FOOD DISTRIBUTION CHAINS

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Abstract

This quantitative study investigated how HACCP and ISO 22000–aligned food safety management systems enhanced biosecurity performance across global food distribution chains. The analysis used a multi-country, multi-node dataset comprising 120 firms, 286 facilities, 412 international routes, 1,034 suppliers, and 6,480 shipments. Firms were distributed across HACCP-only (30.0%), ISO-only (25.8%), integrated HACCP–ISO (29.2%), and low-maturity baseline chains (15.0%). High-risk commodities represented 58.5% of shipments, and cold-chain dependency averaged 0.64, indicating extensive exposure to temperature-sensitive biosecurity risks. Preventive capability was operationalized through HACCP maturity, ISO maturity, and integration depth indices, all of which demonstrated strong reliability (a = 0.88–0.91) and coherent factor structure. Descriptively, integrated chains showed the strongest preventive profiles (HACCP maturity M = 4.12; ISO maturity M = 4.05; integration depth M = 4.21) and the most favorable outcomes, including microbial compliance of 94.3% and only 1.8 CCP deviations per 100 shipments, compared with 86.1% compliance and 5.7 deviations in baseline chains. Multilevel regressions indicated that HACCP maturity predicted higher microbial compliance ($\beta = 0.24$, $p < .001$) and fewer CCP deviations ($\beta = -0.31$, $p < .001$), while ISO maturity independently improved compliance ($\beta = 0.19$, $p < .001$) and reduced recalls or border rejections ($\beta = -0.23$, $p < .001$). Integration depth added further explanatory power across all outcomes, especially CCP deviations ($\beta = -0.18$, $p < .001$) and supplier nonconformity dispersion ($\beta = -0.21$, $p < .001$). Final models explained substantially more variance than baseline risk controls alone (R^2 rising from 0.12–0.25 to 0.30–0.44). Overall, higher HACCP and ISO maturity, reinforced by deep integration, aligned with stronger, more stable chain-wide biosecurity in multinational distribution corridors.

Keywords

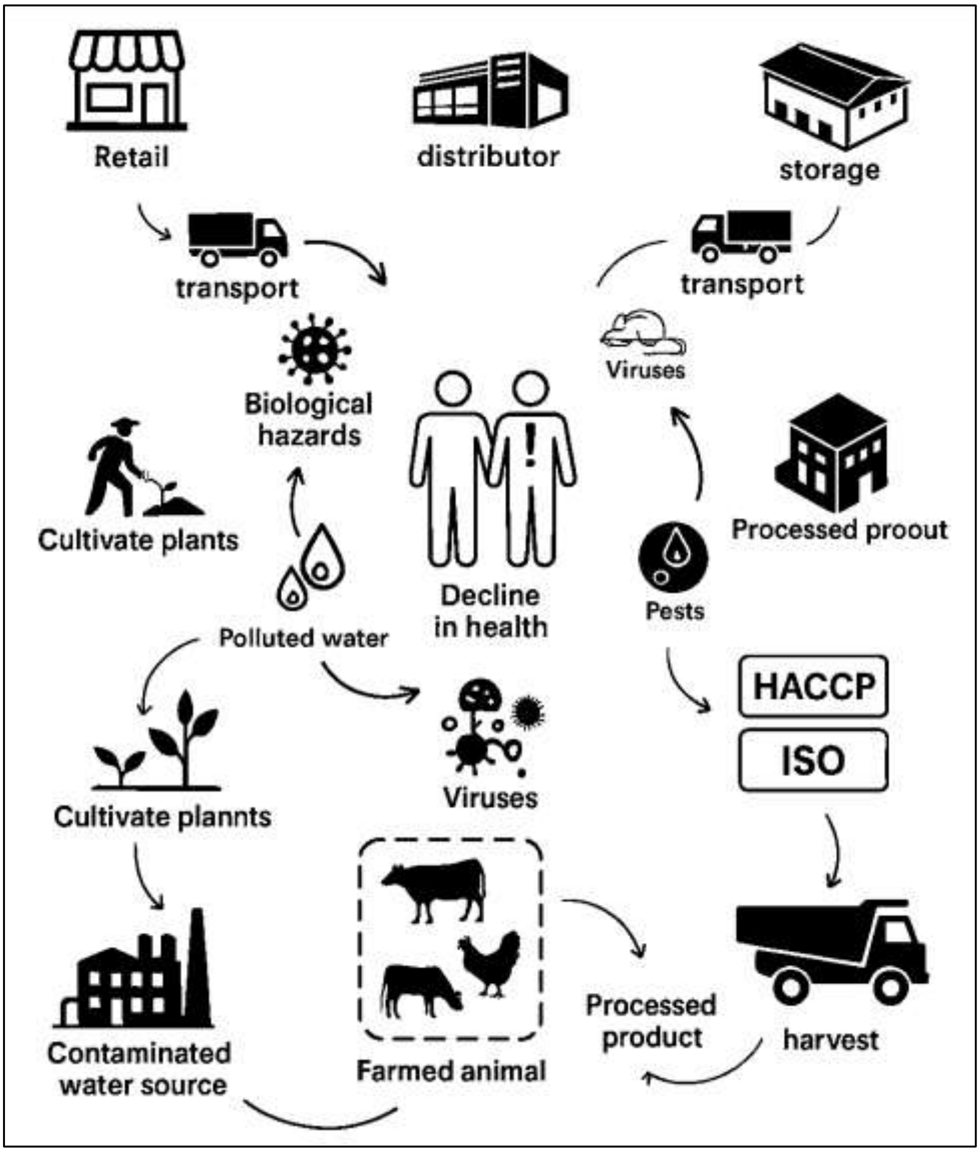
HACCP; ISO 22000; Biosecurity; Food Distribution Chains; Cold Chain Integrity.

INTRODUCTION

Food biosecurity in global food distribution chains refers to the organized prevention and control of biological hazards that can enter, persist, or spread as food moves from production through processing, storage, transport, retail, and consumption (Malik et al., 2021). Biological hazards include bacteria, viruses, parasites, molds, and toxins of biological origin that threaten public health, disrupt trade, and erode consumer confidence. Global distribution chains are now dense, multi-tiered networks in which ingredients and finished foods cross multiple borders, climates, and handling environments before reaching end users. This scale and complexity create repeated opportunities for contamination through temperature abuse, cross-contact, poor hygiene, pest intrusion, unsafe water, and compromised packaging. Biosecurity is therefore a supply-chain property rather than a site-limited concern: it depends on preventive barriers that operate consistently at every node, including farms, abattoirs, processing plants, cold stores, transport fleets, ports, wholesale markets, supermarkets, and food service. International significance arises because foodborne hazards do not respect national boundaries; outbreaks and contamination events can rapidly propagate through export channels, triggering cross-country recalls, border rejections, and cascading economic losses (Fortin et al., 2021). In this environment, harmonized preventive systems provide the most practical route for aligning hazard control across diverse legal regimes and organizational cultures. Two frameworks dominate this preventive landscape: Hazard Analysis and Critical Control Points (HACCP) and the International Organization for Standardization (ISO) management standards for food safety and supply-chain assurance. HACCP supplies the scientific logic for identifying hazards, locating points of highest control leverage, and defining measurable limits and monitoring. ISO frameworks supply the management architecture for making those controls stable, auditable, and communicable across organizations and borders. Quantitative scholarship across many commodities and regions repeatedly shows that formal preventive systems lower microbiological failure rates and strengthen operational discipline in distribution. The widespread incorporation of these systems into public regulation and private certification has made them a common language of biosecurity in global food trade (Pandhi et al., 2023). A quantitative introduction to HACCP and ISO as biosecurity tools must therefore begin with clear definitions, the roles they play at multiple supply-chain layers, and the measurable outcomes through which their effectiveness is evaluated.

HACCP is a preventive, science-based system that organizes food safety around hazard prediction and control rather than end-product testing alone (Rigos & Kogiannou, 2023). The framework is operationalized through seven principles: conducting hazard analysis, identifying critical control points, establishing critical limits, creating monitoring procedures, defining corrective actions, verifying system performance, and maintaining documentation. In distribution chains, these principles translate into a structured barrier strategy. Hazard analysis identifies biological threats linked to raw materials, processing environments, human handling, equipment surfaces, air and water inputs, pests, and transport conditions. Critical control points are then selected where hazards can be prevented or reduced most efficiently, such as thermal processing steps, chilling and freezing stages, segregation zones, sanitation cycles, and shipment temperature management (Chen et al., 2020). Critical limits provide numerical thresholds—time–temperature targets, microbial tolerances, sanitizer concentrations, or humidity bands—so that control is verifiable. Monitoring generates real-time evidence that limits are met, often using calibrated sensors, test kits, and inspection routines. Corrective actions define containment and recovery steps when limits are breached, including product isolation, deep cleaning, equipment repair, supplier suspension, and route reassignment. Verification ensures that monitoring and corrective actions truly control hazards by combining trend checks, independent sampling, and process validation. Documentation supports traceability and accountability across chain partners. Research spanning meat, seafood, dairy, produce, spices, ready-to-eat foods, and refrigerated logistics converges on the finding that HACCP reduces pathogen prevalence and nonconforming lots when CCP selection and monitoring are well matched to process realities (Overbosch & Blanchard, 2023). Quantitative evaluations also show that the magnitude of risk reduction depends on the accuracy of hazard modeling and on how tightly critical limits reflect actual process variability. In long chains, HACCP has expanded from factory floors to warehouses, vehicles, and retail handling, where biological hazards can re-emerge after processing. This expansion highlights HACCP's adaptability as a biosecurity tool: it converts microbiological knowledge into operational controls that travel with the product through every transfer point in the global distribution system.

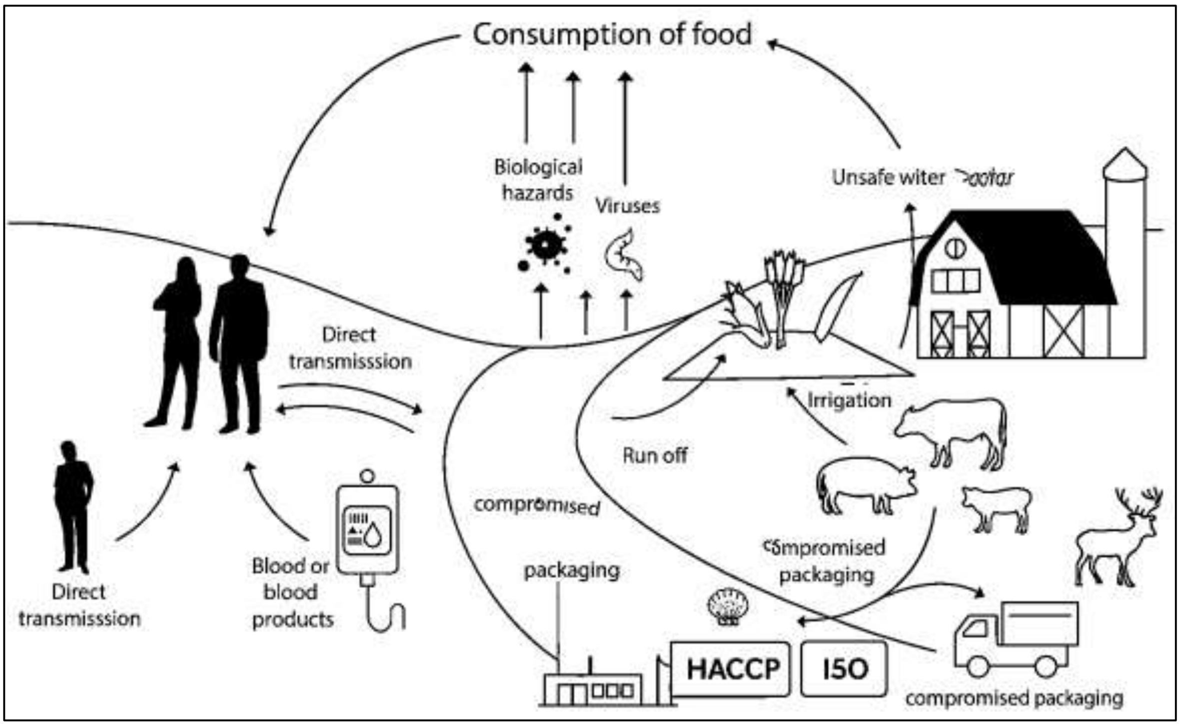
Figure 1: Food Biosecurity Across Global Chains



ISO frameworks for food safety and supply-chain management build on HACCP by embedding hazard control within a standardized management system. The most prominent food safety standard in this family is ISO 22000, which requires organizations to apply HACCP principles inside a broader system of leadership responsibility, risk-based planning, competence management, internal communication, operational control, verification, corrective action, and continual review (Zimon et al., 2020). The value of this structure for biosecurity lies in its capacity to reduce inconsistency across sites and partners. Distribution chains often involve multiple facilities operating under different languages, labor markets, and regulatory expectations. ISO requirements for documented procedures, training, role clarity, and audits make hazard controls repeatable rather than dependent on individual discretion. ISO also emphasizes prerequisite programs such as sanitation, pest control, water safety, allergen management, equipment maintenance, personnel hygiene, and transport cleanliness. These prerequisites serve as foundational biosecurity barriers that prevent hazard introduction and multiplication outside specific CCPs. Many organizations also align ISO 22000 with other ISO standards that reinforce traceability, risk assessment, environmental hygiene, and cargo security (Okpala & Korzeniowska, 2023). Empirical studies across regions show that ISO-based systems increase audit performance, reduce recurring nonconformities, and strengthen corrective-preventive action discipline. Comparative evidence indicates that organizations using ISO management routines alongside HACCP create more reliable verification cycles and more complete hazard documentation, allowing faster detection of microbial drift and more credible demonstrations of control to foreign buyers and regulators. Private global certification programs often benchmark their requirements against ISO-compatible systems, which further spreads ISO logic through multinational supply chains (Lu et al., 2021). Thus, ISO frameworks act as the managerial infrastructure that stabilizes HACCP hazard control across the entire distribution network, making biosecurity a system attribute rather than a collection of isolated plant-level practices. Biosecurity improvement can be understood more precisely when HACCP is treated as the technical engine of hazard control and ISO standards are treated as the governance engine that keeps that control coherent across the chain. Global food distribution includes upstream farming and consolidation, midstream processing and packaging, and downstream logistics and retail (Pearson et al., 2019). Each stage has distinct biological risks and different degrees of control leverage. HACCP provides a method for tailoring hazard controls to those contexts, while ISO requires shared communication and documented interfaces so that controls remain compatible across tiers. Evidence from supply-chain safety research shows that upstream hazard identification becomes more accurate when it incorporates feedback from downstream failures, and documented inter-organizational communication is the mechanism that allows this. A recurring quantitative finding is that distribution hazards frequently emerge from weak supplier alignment, variable sanitation practices, or inconsistent temperature management during transit. ISO-driven supplier approval and verification routines reduce these weaknesses by requiring proof of prerequisite compliance, systematic risk ranking of suppliers, and clear rules for corrective escalation (Gunawan et al., 2019). At operational level, HACCP monitoring provides data streams—temperature logs, sanitation records, microbial tests, and deviation counts—that ISO uses in audits and management reviews to drive disciplined correction. Several large-scale assessments show that integrated systems yield lower variation in compliance between facilities, which matters because a long chain is only as safe as its weakest link. Studies on cargo and transit security add that management standards focusing on access control, sealed loads, route risk analysis, and tamper detection can reduce biological contamination opportunities during transport and at borders. When these security routines are aligned with HACCP hazard maps, they become biosecurity barriers for both unintentional and intentional contamination. Across many sectors, the integrated approach delivers layered defense: technical CCP controls constrain hazard behavior, while governance routines sustain those controls through standardization, learning, and accountability (Tsoukas et al., 2022). This layered defense is central to quantitative modeling of biosecurity because it bridges micro-level process control with macro-level supply-chain stability.

International regulation and market governance amplify the role of HACCP and ISO in shaping biosecurity outcomes. Many countries require preventive controls for high-risk foods, and public inspection systems increasingly evaluate firms based on their hazard analysis and CCP control rather than detached end-product checks. Simultaneously, multinational buyers expect suppliers to demonstrate preventive system certification as proof of biosecurity capability (Dasaklis et al., 2022). Research on trade access indicates that certified preventive systems support easier entry into strict markets and reduce border rejection rates. This effect is not only a matter of formal compliance; it reflects reduced information asymmetry. Buyers importing food from distant regions cannot observe day-to-day practices, so audited HACCP-ISO systems serve as credible signals of control. Studies on governance costs show that harmonized preventive systems lower transaction friction by providing a common audit language for suppliers, logistics firms, and retailers operating under different laws. Biosecurity threats in global trade include classic foodborne pathogens as well as transboundary risks that ride on traded goods and transport environments (Zhao et al., 2020). Preventive system alignment offers practical control against these threats by enforcing shared risk assessment logic and standardized documentation across borders. Quantitative adoption studies also show systematic variation in preventive system intensity linked to enforcement strength, purchaser requirements, firm size, and training capacity. Such variation creates a natural basis for statistical testing of how implementation depth relates to biosecurity performance (Yadav et al., 2021). Evidence from outbreak investigations and recall analytics converges on the observation that organizations with robust preventive programs respond faster, isolate hazards more precisely, and restore trade confidence more efficiently. In effect, HACCP provides the operational grammar of hazard control, while ISO provides the institutional grammar for demonstrating that control in international arenas. This regulatory and market embedding makes HACCP and ISO foundational biosecurity infrastructures in global distribution chains, supporting quantitative inquiries into how they influence measurable safety and security indicators at scale (Zhao et al., 2020).

Figure 2: Food Biosecurity Through Global Supply chains



The core objective of this quantitative study is to examine how the combined implementation of HACCP and ISO-based food safety management frameworks enhances biosecurity performance across global food distribution chains. Specifically, the study aims to measure the extent to which HACCP's hazard identification, critical control point design, critical limit enforcement, monitoring discipline, corrective action reliability, and verification routines contribute to reducing biological hazard events during storage, transport, and cross-border handling. In parallel, it seeks to evaluate how ISO management system elements—documented prerequisite programs, supplier approval and verification, competency and training systems, internal and external communication controls, audit cycles, equipment calibration, and management review—stabilize and standardize HACCP application across multiple facilities and logistics partners operating in different regulatory and cultural contexts. A central objective is to quantify the relationship between HACCP–ISO integration depth and measurable biosecurity outcomes at facility, route, and network levels, using indicators such as microbial compliance rates at destination, frequency and duration of temperature excursions, sanitation and pest-control nonconformities, incidence of product holds or rejections, recall occurrence, and variability in supplier compliance. The study also aims to compare biosecurity performance between distribution chains that apply HACCP alone, ISO-aligned systems alone, and fully integrated HACCP-within-ISO systems, to determine whether integration yields statistically significant improvements in hazard control reliability and consistency across nodes. Another objective is to model how contextual drivers—such as chain length, commodity risk profile, cold-chain dependency, shipment volume, border transition intensity, and certification surveillance frequency—moderate the effectiveness of HACCP and ISO frameworks in real distribution environments. By constructing an empirical dataset that links implementation maturity scores with outcome metrics, the study intends to identify which specific technical controls and management practices are the strongest predictors of biosecurity enhancement in multinational supply networks. Ultimately, the objective is to generate a robust, evidence-based explanation of how preventive hazard control (HACCP) and system governance standardization (ISO) interact to reduce biological risks, strengthen traceability-ready control, and maintain stable safety performance as food products move through complex global distribution corridors.

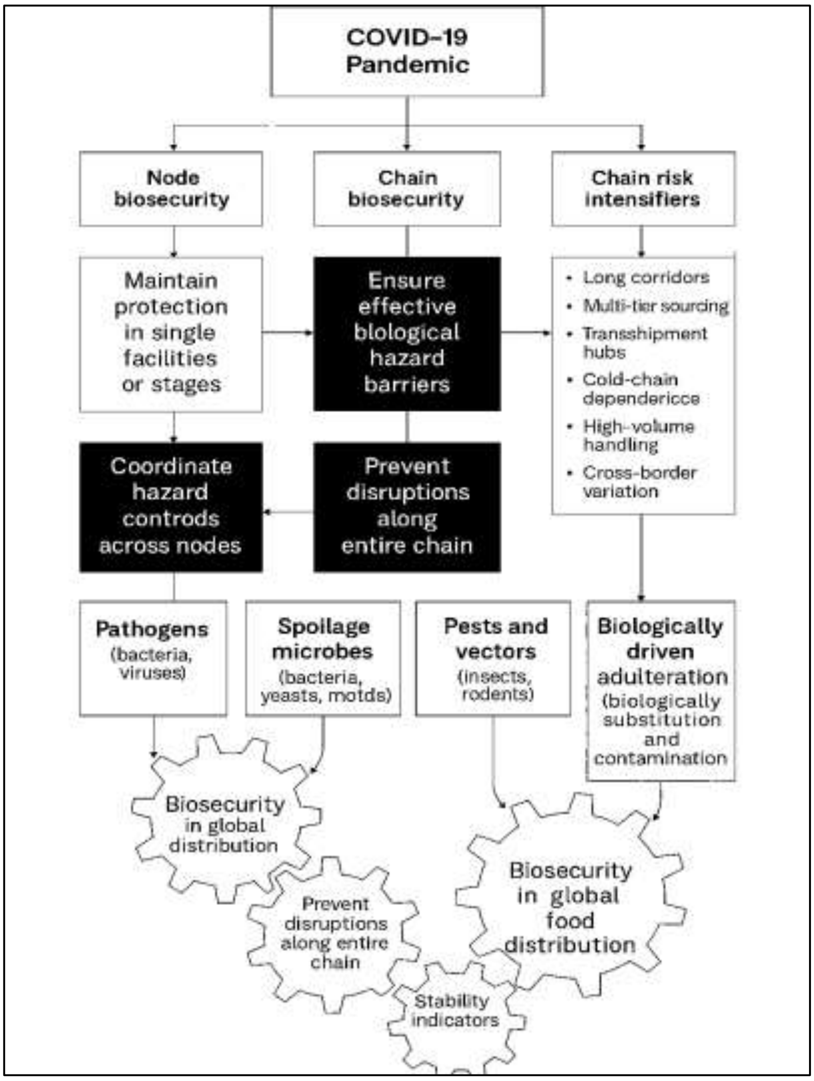
LITERATURE REVIEW

The literature on biosecurity in global food distribution chains converges on the idea that biological hazards are best controlled through preventive, system-wide governance rather than isolated end-point inspection (Renault et al., 2021). As food moves through transnational supply networks—spanning production, processing, cold storage, transport, border transitions, wholesale, and retail—hazard opportunities multiply through temperature excursions, cross-contamination vectors, personnel handling, and supplier variability. Preventive frameworks therefore function as chain-level "risk architectures" that define how hazards are identified, controlled, verified, and communicated across nodes. Two dominant frameworks underpin this architecture: HACCP, which provides a structured hazard-control method based on critical control points and measurable limits, and ISO food safety management standards, particularly ISO 22000, which embed HACCP logic within a unified management system emphasizing prerequisite programs, documentation, auditing, communication, and performance evaluation across the food chain (Ravi et al., 2019). ISO guidance explicitly positions ISO 22000 as a supply-chain integrity standard built around preventing weak links and harmonizing safety expectations across participating organizations. The empirical literature further indicates that integrating HACCP into ISO-based management systems yields stronger and more consistent safety outcomes than fragmented adoption, because ISO strengthens policy alignment, verification routines, and continuous control reliability across sites and partners. At the same time, quantitative studies show uneven implementation depth, variation in audit performance, and differing hazard outcomes by commodity type, cold-chain reliance, and trade intensity (Barker & Francis, 2021). This literature review synthesizes theoretical and empirical research on HACCP effectiveness, ISO-based FSMS performance, and their integrated role in enhancing biosecurity in global distribution, with emphasis on measurable implementation constructs, validated performance indicators, and statistically testable relationships required for robust quantitative modeling.

Biosecurity in Global Food Distribution

Biosecurity in global food distribution chains is commonly defined in the literature as the systematic prevention of the introduction, survival, and spread of biological hazards as food travels through interconnected supply nodes (Pavez et al., 2019). Scholars frame biosecurity as an active, preventive posture rather than a reactive inspection activity, emphasizing that hazards emerge not only at the point of production but across processing, storage, transportation, wholesale, retail, and food-service interfaces. A recurring conceptual distinction is made between node biosecurity and chain biosecurity. Node biosecurity describes localized protection within a single facility or stage, such as a farm, processing plant, warehouse, or vehicle. Chain biosecurity, by contrast, is treated as an emergent system-level property shaped by coordination across all nodes and handoffs. This distinction matters because isolated excellence at a single node cannot guarantee overall chain integrity if weak links persist elsewhere. Research on supply-chain risk repeatedly shows that biological hazards exploit discontinuities—moments where products, people, equipment, or information move between actors (Militzer et al., 2023). Within distribution-focused biosecurity, hazard categories are typically grouped into four interrelated domains. First are foodborne pathogens, including bacteria, viruses, and parasites that can cause acute outbreaks and cross-border public health emergencies. Second are spoilage microorganisms that may not always cause illness but degrade quality, increase food waste, and erode consumer trust through sensory deterioration. Third are pests and vectors that infiltrate through storage environments, transport containers, or mixed cargo and then contribute to contamination or commodity loss. Fourth are biologically driven adulteration events, which include intentional or opportunistic substitution and contamination of biological origin that exploit vulnerabilities in traceability and verification (Lugo-Morin, 2020). Across many empirical contributions, these hazards are described as distribution-amplified because they can re-emerge or intensify after processing through time–temperature abuse, cross-contact, or compromised hygienic conditions during movement. The conceptual foundation therefore positions biosecurity as a multi-hazard, multi-node governance challenge where prevention depends on synchronized controls, shared standards, and reliable evidence of compliance across the whole chain rather than at isolated points (Black & Bartlett, 2020).

Figure 3: Conceptual Framework for Food Biosecurity



The global characteristics of modern food distribution chains intensify biosecurity risk in ways that are repeatedly emphasized across international supply-chain and food-safety research. One widely documented contributor is the length and geographic span of logistics corridors (Dittrich et al., 2021). Long-distance shipment expands the time window in which microorganisms can grow, toxins can accumulate, or pests can infiltrate, particularly when products pass through multiple storage environments and climate zones. Multi-tier sourcing further magnifies risk because inputs can originate from diverse producers operating with different biosecurity capabilities, hygiene cultures, and enforcement contexts. Distribution routes often include consolidation sites and transshipment hubs where cargo is broken down, repacked, or co-loaded, increasing cross-contamination opportunities through shared surfaces, pallets, airflows, and personnel (Ampadu-Ameyaw et al., 2021). Another chain feature linked to elevated biological risk is heavy dependence on cold-chain integrity. Studies across seafood, meat, dairy, produce, and ready-to-eat foods consistently show that microbial behavior is highly sensitive to small temperature deviations, meaning that cold-chain failures can rapidly transform low-risk loads into high-risk ones. High-volume handling also matters. Large-scale distribution relies on fast loading, sorting, and repacking, which can outpace hygiene controls when staffing, training, or equipment sanitation are insufficient. In addition, cross-border regulatory heterogeneity is recognized as a structural risk driver. Distribution chains traverse jurisdictions with different microbial standards, inspection rigor, acceptable limits, and enforcement mechanisms (Guru et al., 2023). Even when hazard control frameworks are aligned, the interpretation of compliance can vary, producing gaps that hazards can exploit. Audit fragmentation compounds this heterogeneity: suppliers and logistics providers may face different certification schemes, checklists, or buyer requirements across markets, which limits the consistency of biosecurity practice. The literature also points to systemic vulnerabilities arising from information discontinuities, such as delayed reporting of deviations, weak incident communication between partners, or incomplete traceability documentation. These chain characteristics, taken together, portray global distribution as a dynamic risk environment where biosecurity depends on maintaining preventive controls through distance, time, repeated handling, and complex governance structures (Canfield, 2023). Biosecurity is thus conceptualized not only as hazard control but also as resilience against disruption created by scale and international variation.

Because biosecurity is a system-level property, scholars emphasize early definition of measurable outcome domains to align evaluation across nodes. One major domain is microbiological outcomes. Distribution-focused studies typically operationalize these as pass/fail rates against microbial criteria, prevalence of specific pathogens at destination testing, or indicator organism levels that reflect hygiene performance (Abdulla & Ibne, 2021; Akram et al., 2023). These measures are treated as direct signals of biological hazard control effectiveness across the chain. A second domain is process outcomes, which capture whether preventive mechanisms are functioning as designed (Ara, 2021; Habibullah & Foysal, 2021). Research on preventive systems uses indicators such as deviation frequency at critical control points, monitoring compliance rates, and nonconformities in prerequisite programs like sanitation, pest control, and transport hygiene (Sarwar, 2021; Musfiqur & Saba, 2021). Process outcomes are valued because they show control reliability even when microbial outcomes are still within limits, enabling earlier detection of risk drift. A third domain is event outcomes, which represent system failures significant enough to trigger visible disruptions (Gardner et al., 2021; Redwanul et al., 2021; Reza et al., 2021). Distribution research commonly tracks recall counts per year, border rejection rates, confirmed contamination incidents, spoilage losses, or product holds and withdrawals. These events are structurally important because they affect both public health and trade continuity. A fourth domain is stability outcomes, which assess consistency rather than absolute performance (Saikat, 2021; Shaikh & Aditya, 2021). In multi-country chains, stability is measured through variability of compliance across sites, routes, and partners, recognizing that a chain's risk is shaped by unevenness. High variance indicates that some nodes or partners remain weak links even when average performance looks acceptable (Animasaun et al., 2023; Amin, 2022). Across many empirical contributions, these outcome domains are shown to be interdependent: unstable process performance often precedes microbiological failure, and event outcomes typically represent the endpoint of prolonged process and stability weaknesses. The literature therefore frames quantifiable outcomes as layered evidence microbial indicators show biological reality, process indicators show operational discipline, event indicators show systemic breakdown, and stability indicators show how evenly biosecurity is distributed (Ariful & Ara, 2022; Nahid, 2022). This multi-domain perspective is crucial for distribution chains because hazards can be controlled in one segment while drifting in another. Measuring biosecurity through only one domain can misrepresent real risk, so researchers increasingly advocate composite outcome perspectives that match the chain-level nature of biosecurity (Hossain & Milon, 2022; Mominul et al., 2022).

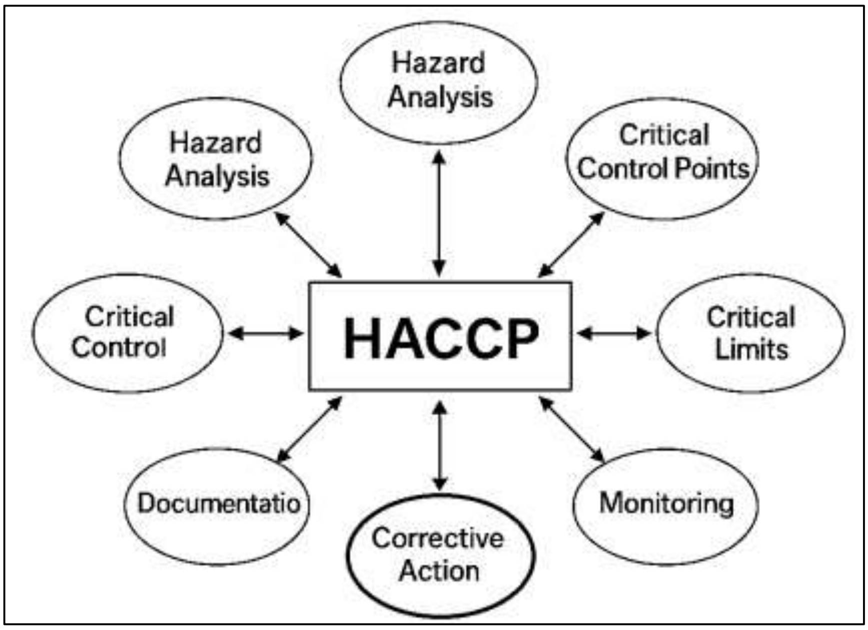
Synthesizing the conceptual foundations, chain risk intensifiers, and outcome domains yields a coherent literature-based framing of biosecurity for global food distribution (Yadav et al., 2020). The field portrays biosecurity as a preventive governance system aimed at ensuring biological hazard barriers remain effective through every transfer point. The node-versus-chain distinction clarifies that biosecurity cannot be fully understood by observing isolated facilities; instead, it is the cumulative product of linked hazard controls, consistent standards, and reliable communication across actors. The hazard categories emphasized—pathogens, spoilage microbes, pests/vectors, and biologically driven adulteration—are treated as distribution-sensitive, meaning they are shaped by logistics conditions and chain governance. Long corridors, multi-tier sourcing, transshipment hubs, cold-chain dependence, high-volume handling, and cross-border regulatory variation intensify risk by increasing exposure time, multiplying handoffs, and widening compliance gaps (Mortuza & Rauf, 2022; Rakibul & Samia, 2022; Tambo et al., 2023). These realities explain why modern scholarship ties biosecurity to both technical control and organizational coordination. The quantifiable outcome domains then make this framing testable. Microbiological indicators provide direct evidence of hazard presence or absence at destination(Saikat, 2022; Kanti & Shaikat, 2022). Process indicators provide evidence of whether preventive controls are executed correctly and consistently along the chain. Event indicators reveal rare but high-impact failures that disrupt health and trade. Stability indicators reveal whether reliability is evenly distributed or concentrated in a few strong performers while weak links persist. Across studies in diverse commodities and regions, authors repeatedly show that the strongest biosecurity systems are those that combine high microbial compliance, low process deviations, minimal disruptive events, and low variability between partners (Arfan et al., 2023; Ara & Onyinyechi, 2023; Jeger et al., 2021). This synthesis positions biosecurity enhancement in distribution chains as a measurable, system-wide achievement rooted in prevention, consistency, and aligned control behavior. It also establishes a clear platform for subsequent literature sections in a quantitative study by defining what biosecurity means, why the global chain environment escalates biological risk, and how success should be operationally observed without relying on speculative or forward-looking claims.

HACCP as a Technical Biosecurity Control Framework

HACCP is widely treated in food safety and supply-chain scholarship as a distinctly technical biosecurity control framework because it converts biological hazard knowledge into operational barriers that can be measured, audited, and improved (Awuchi, 2023). The seven HACCP principles are not described only as procedural steps; they are framed as measurable technical controls whose quality determines whether hazards are prevented from entering or spreading through distribution nodes. Hazard analysis quality is discussed in terms of how comprehensively hazards are identified across ingredients, environments, equipment, personnel practices, storage atmospheres, and transport conditions, and how specifically they are articulated as actionable hazard–product–process combinations. Studies consistently argue that hazard analysis must also rank hazards by probability and severity so that control resources are concentrated on true biosecurity priorities rather than on low-impact risks. CCP adequacy is then defined as the alignment between selected critical control points and the highest-risk stages in a given chain (Sameen et al., 2023). For global distribution, literature stresses CCPs tied to thermal lethality steps, rapid cooling or freezing, cold storage, loading interfaces, vehicle temperature control, sanitation transitions, and segregation points where cross-contamination is most likely. Critical limit precision is portrayed as both a numerical clarity issue and a biological validity issue: limits must be expressed as unambiguous measurable thresholds, and these thresholds must match the biological behavior of the hazard in that process context. Monitoring rigor is conceptualized through the consistency and frequency of checks, the use of real-time instruments where needed, calibration reliability, and record completeness, because monitoring is the evidence channel that links limits to real hazard conditions. Corrective action reliability is described as the speed and accuracy with which deviations are contained and remediated, including how effectively unsafe product is isolated, how quickly root causes are eliminated, and how consistently corrective responses are repeated across shifts and sites. Verification strength is treated as the independence and depth of proof that the system works, including validation of critical limits, periodic sampling, trend analysis of deviations, and structured review of monitoring behavior (Owusu-Apenten & Vieira, 2022). Across this technical framing, authors repeatedly emphasize that HACCP does not function through any single principle; rather, it operates as an integrated control architecture. A strong hazard analysis enables correct CCP selection, correct CCP selection enables meaningful limits, meaningful limits enable purposeful monitoring, purposeful monitoring triggers effective corrective action, and effective corrective action is sustained through verification. This integrated logic is why HACCP is regularly presented as a technical biosecurity system capable of traveling across chain nodes and preventing biological hazards from amplifying during distribution.

Quantitative evidence on HACCP effectiveness across high-risk commodities and export-oriented supply chains consistently reports measurable reductions in biological hazard indicators and compliance failures when HACCP is implemented with high fidelity (Awuchi, 2023). Studies in seafood, meat, poultry, dairy, fresh produce, and ready-to-eat foods show that HACCP adoption is associated with improved microbiological conformity at destination, lower detection rates of regulated pathogens, fewer sanitation-related failures, and more stable temperature control in refrigerated distribution. Facility-level evaluations often document declines in indicator organism loads or pathogen prevalence after HACCP deployment, particularly where CCPs are tied to biologically dominant steps such as cooking, pasteurization, cooling, hygienic packaging, and cold-chain transfer points. In export chains, research indicates that HACCP improves shipment acceptance and reduces border rejection events by providing structured evidence of hazard control that aligns with importing-market requirements. Several quantitative syntheses suggest that the greatest improvements occur when CCP design is narrow and biologically focused, because targeted CCPs reduce monitoring noise and sharpen corrective action response (Militzer et al., 2023).

Figure 4: HACCP Maturity for Chain Biosecurity



Effect magnitudes differ across studies, but the direction of findings remains stable: preventive hazard control shifts safety assurance upstream, producing fewer high-severity deviations downstream. The literature also identifies moderators that repeatedly shape HACCP impact. Training intensity is one of the most consistent moderators, because hazard analysis accuracy, monitoring discipline, and corrective response quality depend on staff competence and sustained role clarity. Process complexity is another moderator; multi-ingredient, multi-step, or highly seasonal chains show weaker gains unless hazard analysis is granular and CCPs are prioritized by risk rather than by routine. Enforcement intensity and buyer surveillance are also noted moderators, as stronger oversight increases monitoring reliability, reduces paper-only practices, and produces larger hazard reductions. Researchers further observe that HACCP effectiveness is enhanced where organizations use monitoring data to revise hazard analysis and recalibrate limits, creating feedback-driven technical learning (Ferri et al., 2023). Across the evidence base, HACCP is therefore treated not merely as a regulatory checklist but as a measurable preventive capability whose effectiveness can be observed through microbial outcomes, process compliance patterns, export integrity indicators, and reduced incidence of disruptive biosecurity events throughout global distribution.

At the same time, the literature is clear about persistent HACCP implementation gaps that weaken biosecurity outcomes, especially in long, multi-node distribution chains. One frequently documented gap is CCP misidentification, where plans select CCPs based on inherited templates or convenience rather than on chain-specific biological risk logic (Stentiford et al., 2022). Misidentification leaves true high-risk steps insufficiently controlled, while over-identification creates too many CCPs and dilutes monitoring focus, ultimately lowering control sensitivity. Weak monitoring practices form another recurring problem across audits and quantitative assessments. Researchers describe patterns such as incomplete logs, monitoring that occurs too infrequently during critical risk windows, reliance on uncalibrated instruments, and retrospective record filling that converts monitoring into paperwork rather than hazard detection. These weaknesses are strongly associated with cold-chain temperature excursions, sanitation drift in warehouses, and downstream microbial failures that appear late in the chain. A third gap is paper compliance, in which HACCP documentation exists but hazard analysis is rarely updated, critical limits are copied without evidence, and verification relies on checklist completion rather than independent confirmation (Blagojevic et al., 2021; Mushfequr & Ashraful, 2023; Shahrin & Samia, 2023). Paper compliance is repeatedly described as particularly dangerous for biosecurity because it masks real hazard trajectories and delays corrective actions until failures become visible through recalls, spoilage losses, or border rejections. Another major weakness highlighted in distribution-centered research is the under-representation of post-processing hazards in HACCP plans. Historical HACCP practice often concentrates on processing lines, so biological risks emerging during loading, transshipment, transport, cross-docking, retail holding, or mixed-cargo storage may be treated only as general hygiene expectations rather than as hazard-specific controls. This omission leaves critical risk windows unmanaged, especially for chilled and ready-to-eat goods that remain microbially sensitive after processing. Studies also note that inadequate integration between suppliers and downstream nodes weakens hazard analysis, because incoming risk variability is not fully reflected in CCP design (Mustafa, 2023). When these gaps coincide, hazards exploit the resulting blind spots: a shallow hazard analysis leads to weak CCP selection, weak CCP selection leads to irrelevant limits, irrelevant limits make monitoring unreliable, unreliable monitoring delays corrective action, and superficial verification prevents learning. The literature thus portrays HACCP gaps as structural underminers of chain biosecurity rather than minor compliance errors.

Synthesizing the technical principles, the quantitative evidence, and the recurring gaps, scholarship frames HACCP maturity as the central concept for explaining differences in biosecurity performance across global food distribution chains (Scollo et al., 2023). HACCP maturity refers to the degree to which the system is executed as an integrated technical architecture: hazards are comprehensively identified and prioritized; CCPs are biologically aligned to actual high-risk steps across production and distribution; critical limits are precise and defensible; monitoring is frequent, instrument-supported, and fully recorded; corrective actions are rapid, containment-focused, and root-cause oriented; and verification is independent, trend-driven, and improvement-linked. Researchers emphasize that maturity is not a yes–no state; it varies by depth of implementation, resource allocation, and how actively monitoring data are used for system refinement. Because each HACCP principle produces observable evidence—through audits, monitoring logs, deviation records, corrective action histories, and verification reports—maturity is repeatedly treated as a latent technical capability that predicts hazard reduction more strongly than any individual principle (Zema et al., 2022). In high-risk distribution systems, this latent framing is especially helpful because biosecurity failures are rarely caused by a single missing step. Failures emerge from interacting weaknesses that compound across nodes and time. Conversely, when maturity is high, the principles reinforce one another to create layered defenses that travel with the product across storage, transport, and retail environments, keeping hazards from amplifying in transit. Quantitative studies using multi-item HACCP scales show that a unified maturity factor explains variation in microbial compliance, deviation frequency, shipment acceptance, recall incidence, and stability of safety performance across sites and partners (Butcher et al., 2021). This body of work positions HACCP as a measurable technical biosecurity capability for global distribution chains, where maturity operates as the clearest bridge between preventive system quality and observed reductions in biological hazard events across complex, transnational food networks.

ISO Frameworks as Chain-Level Biosecurity Governance

ISO frameworks, especially ISO 22000, are widely positioned in the literature as chain-level biosecurity governance because they extend hazard prevention beyond isolated facilities and embed it within an auditable management system that can be shared across partners (Anestis et al., 2023). ISO 22000 is structured around a management cycle that requires top leadership to define and maintain a food safety policy, set clear responsibilities, allocate resources, and routinely evaluate performance. Leadership commitment is treated as a measurable governance component because it determines whether biosecurity controls are prioritized over throughput pressures in distribution settings. Research repeatedly shows that when leadership is visibly engaged—through written policy, resourcing decisions, participation in management review, and enforcement of accountability—compliance becomes consistent across shifts and sites. Another central governance domain is the completeness of prerequisite programs and operational prerequisite programs. These include sanitation regimes, pest and vector control, water and air hygiene, equipment maintenance, allergen safeguards, site zoning, and transport hygiene requirements (Manning, 2019). In distribution chains, PRPs and OPRPs function as the "background barriers" that stop hazards from entering or multiplying outside critical control points. Competency and training coverage is also highlighted as a decisive ISO governance lever, because ISO requires that the organization define competence needs, verify training effectiveness, and maintain records. Studies treat training coverage as measurable through the proportion of trained staff, training hours per role, reassessment frequency, and the degree to which training translates into correct operational behavior. Communication reliability is another governance pillar that ISO formalizes with explicit requirements for internal reporting and external partner notifications. This matters in global chains because hazards frequently propagate through delayed information of temperature deviations, supplier failures, or sanitation lapses; ISO requires structured pathways for timely escalation and documentation of such incidents. Document control and traceability readiness are also core ISO governance components (Black & Bartlett, 2020). ISO expects standardized document creation, controlled revisions, and retrievable records, enabling traceability that supports rapid containment when biosecurity signals appear. Finally, ISO makes auditing a measurable governance engine. Audit frequency, depth, independence, and closure rates for nonconformities are repeatedly emphasized as practical indicators of ISO maturity, because they show how actively the system searches for weak links and how reliably it corrects them. Together, these components frame ISO 22000 not as a technical hazard tool alone, but as a supply-chain governance architecture that aligns people, procedures, communication, and evidence around biosecurity prevention.

Quantitative studies examining ISO-based food safety management systems consistently associate certification with measurable improvements in compliance and hazard-control performance across food organizations embedded in distribution networks. A recurring empirical pattern is that audit and inspection results improve after ISO 22000 adoption, shown through higher conformity scores, fewer major nonconformities, and better prerequisite program verification results (Prasetya et al., 2022). In many facility-level before-and-after evaluations, organizations report reduced frequency of sanitation failures, stronger hygiene monitoring, and fewer deviations in storage or transport conditions once ISO routines are implemented. The literature suggests that these changes are not solely due to the HACCP logic inside ISO, but to the management system's discipline around documentation, training, and accountability. Quantitative work also points to reductions in noncompliance incidents that would otherwise escalate into distribution-level biosecurity disruptions, such as recurrent CCP deviations, incomplete traceability records, or supplier-related failures. In export-oriented and multinational contexts, ISO certification is linked to lower rates of shipment rejection and fewer recall triggers, reflecting stronger preventive reliability across chain handoffs (Benfield et al., 2023). Another measurable effect emphasized is reduction in performance variability between sites. Several multi-site studies find that ISO-based systems narrow the gap between best-performing and weakest facilities by applying the same PRP standards, audit logic, training requirements, and corrective action expectations everywhere. These results are important in global distribution because chain risk is magnified by uneven compliance. Some quantitative contributions also highlight process-efficiency co-benefits of ISO adoption, such as clearer workflow documentation, faster corrective action closure, and improved equipment calibration compliance. These efficiencies indirectly strengthen biosecurity by preventing unnoticed drift in hygiene or cold-chain monitoring. Across the evidence base, ISO's measurable performance effects are strongest when certification is paired with active internal audits and management reviews rather than treated as a one-time market badge (Mazzeo et al., 2022). This supports the view that ISO functions through continuous governance pressure, not simply through the achievement of certification status.

Figure 5: ISO Governance for Chain Biosecurity

ISO's relevance to global biosecurity is further explained in the literature through its role as a mechanism for cross-border harmonization. Global distribution chains must operate across multiple regulatory regimes that differ in microbial criteria, inspection methods, documentation expectations, and enforcement intensity (Lyal & Miller, 2020). ISO provides a standardized governance language that allows companies, auditors, and regulators to interpret hazard control practices in comparable ways, regardless of geography. In multinational chains, this standardization reduces friction because suppliers can align with one auditable framework instead of navigating many incompatible buyer-specific requirements. The literature emphasizes that standardized audit language enables consistent evaluation of PRP performance, CCP evidence, corrective action quality, and traceability readiness across countries. Harmonization effects are also reinforced through ISO's alignment with widely accepted global benchmarking initiatives used by large retailers and importers. When distribution chains treat ISO-compatible certification as a shared qualification threshold, it becomes a market governance tool that pressures all partners toward similar biosecurity routines (Yurkov et al., 2021). Quantitative trade-focused studies note that this harmonization supports smoother supplier onboarding, fewer repeated audits, and faster acceptance of corrective evidence after deviations, which collectively reduce the time hazards remain uncontrolled. Harmonization is also linked to improved communication between partners, because ISO terminology—such as nonconformity classes, corrective-preventive action logic, and PRP verification rules—creates a common way to describe risks and responses. In distribution corridors that include consolidation hubs and transshipment points, harmonized governance reduces the chance that biosecurity controls weaken at interface nodes (Adebola, 2021). Several studies additionally suggest that harmonization improves traceability interoperability, because standardized documentation structures allow participants to connect records across tiers more easily during investigations or recalls. In short, ISO frameworks are presented as a global coordination instrument that transforms biosecurity from a locally interpreted practice into an internationally legible governance system.

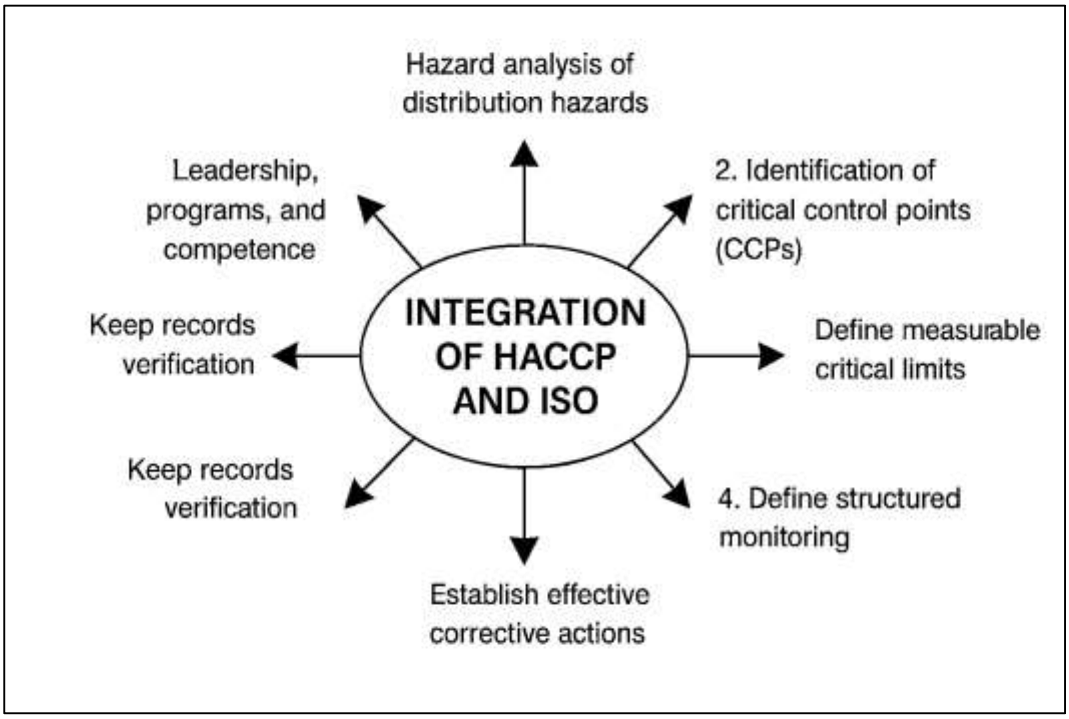
HACCP within ISO Systems

Integration of HACCP within ISO-based food safety management systems is consistently portrayed in the literature as a synergistic biosecurity strategy that binds technical hazard control to chain-wide governance. HACCP is described as the technical core that defines what biological hazards must be controlled and where control is most effective (Awuchi, 2023). The hazard analysis step maps pathogens, spoilage organisms, pests, and biologically based adulteration risks across each processing and distribution stage, while critical control points specify the exact process or logistics steps where those hazards can be prevented or reduced. Critical limits translate that control into measurable thresholds, and monitoring confirms whether real operations remain inside safe boundaries. Corrective actions act as containment barriers when deviations occur, and verification confirms that the entire control logic is working in practice. ISO systems, particularly ISO 22000, are framed differently: they supply the governance and management architecture that keeps HACCP technical controls stable through time, across shifts, and across organizational boundaries (Rath & Ischi, 2020). The literature emphasizes that global distribution chains involve many actors—suppliers, processors, cold stores, carriers, brokers, and retailers—each with its own routines, people, and resource constraints. In that setting, HACCP alone can identify correct controls but cannot ensure that all partners will implement them to the same standard without a shared management system. ISO fills this gap by requiring leadership commitment, controlled documentation, prerequisite programs, competence management, structured communication, internal audits, and continual review (Sorbo et al., 2022). These governance elements are repeatedly described as the reason HACCP becomes chain-capable rather than facility-bounded when embedded within ISO, because they standardize how hazards are discussed, how evidence is recorded, and how deviations are escalated across the entire network.

Empirical comparisons across sectors repeatedly show a performance gradient between HACCP-only, ISO-only, and integrated HACCP-within-ISO adoption, with integrated systems yielding the most reliable biosecurity outcomes. Studies of HACCP-only adoption often report meaningful hazard reduction within individual facilities, especially where CCPs are tightly linked to biologically dominant steps such as cooking, pasteurization, rapid cooling, or cold-chain transfer points (Rath & Ischi, 2019). Yet this same body of work notes that HACCP-only operations frequently display greater variability in control execution across sites, shifts, and partners, largely because technical controls depend on local training quality, management attention, and record discipline. ISO-only adoption tends to strengthen organizational discipline through standard procedures, audits, prerequisite programs, and traceability readiness, but its hazard-control impact is sometimes weaker when HACCP logic is not embedded deeply or when CCP monitoring remains loosely specified (Gałęcki et al., 2023). In integrated adoption, the literature reports more consistent control performance across nodes because governance requirements and technical controls reinforce each other. Commonly observed patterns include stronger verification behavior, fewer recurrent nonconformities, and lower spread in compliance scores between facilities and logistics partners. Integrated adopters also tend to show more stable microbial pass rates at destination and lower deviation counts in cold-chain and sanitation controls during distribution. The comparative narrative stresses that ISO transforms HACCP from a plan that can exist on paper into a living technical system that is repeatedly checked, challenged, and corrected through audits and management review (Chan et al., 2020). As a result, integrated systems are described as better able to prevent hazard amplification at chain interfaces such as supplier handoffs, cross-docking hubs, transshipment points, and retail holding environments, which are repeatedly identified as high-risk windows in global distribution.

The literature explains synergy through a set of linked mechanisms that connect ISO governance features to stronger HACCP technical performance (Bergwerff & Debast, 2021). One mechanism center on audit cycles. ISO requires planned internal audits, independent external audits, and formal management review of audit results. Researchers argue that this recurring scrutiny improves HACCP monitoring discipline by increasing the likelihood that records are completed in real time, instruments are calibrated, monitoring frequency matches risk periods, and deviations are detected rather than hidden. Another mechanism is the standardization and verification of prerequisite programs and operational prerequisite programs. ISO specifies hygiene foundations such as sanitation schedules, pest control systems, equipment maintenance, personnel hygiene, zoning, allergen safeguards, and transport cleanliness (Gonzalez-Fandos et al., 2020). When these foundations are stable and verified, biological background load is lower, which reduces the pressure placed on CCPs and results in fewer critical limit breaches. A third mechanism involves supplier and partner communication. ISO requires structured internal reporting and external notification paths so that hazards, deviations, or control failures are communicated rapidly across tiers. This is described as reducing upstream hazard load and preventing the silent spread of risk, because suppliers receive clearer expectations and downstream actors receive early warning about deviations. A related mechanism discussed less formally but repeatedly observed is learning lock-in: ISO's corrective-preventive action routines compel root-cause investigation and system updates, so HACCP hazard analysis and CCP design are refined using evidence from deviations rather than left static (Laurent et al., 2022). Across these mechanisms, synergy is not portrayed as a vague benefit but as a practical chain-level effect where governance improves the reliability, accuracy, and responsiveness of technical hazard controls.

Figure 6: Integrated HACCP–ISO Biosecurity Framework



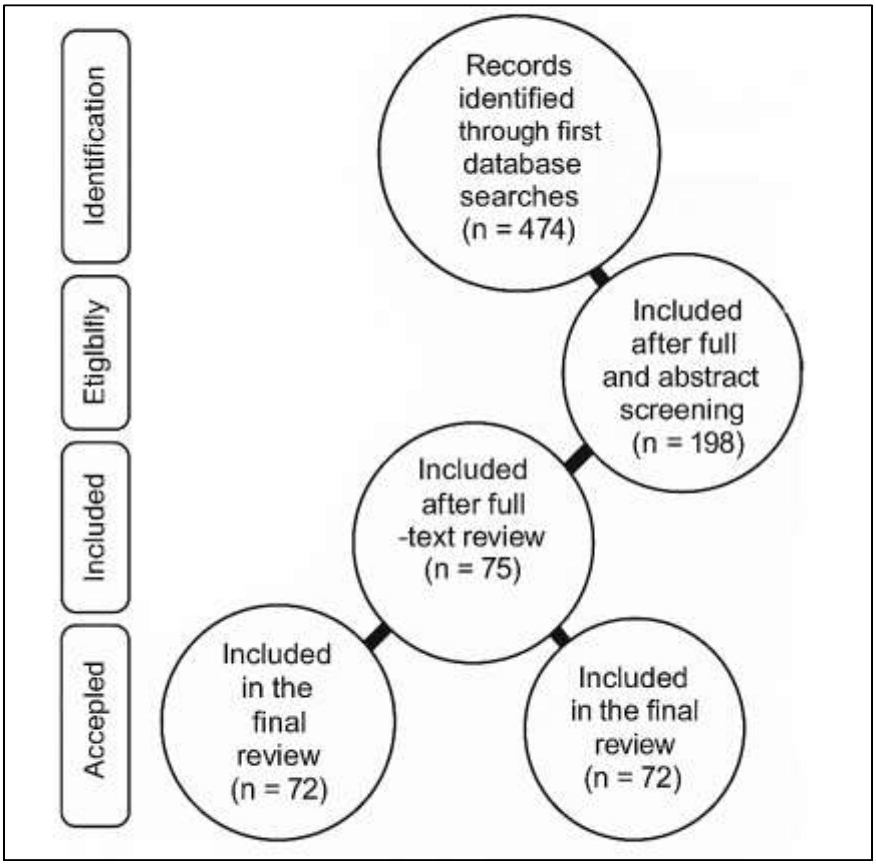
Across these strands, integration depth is treated as the key explanatory construct for synergistic biosecurity effects. Integration depth refers to how fully HACCP is embedded into ISO routines rather than attached as a parallel or symbolic program. Shallow integration is described as a situation where HACCP plans exist, but prerequisite programs are weakly verified, audits do not target CCP effectiveness, corrective actions are slow or inconsistent, and hazard analysis is rarely updated (Maksimović et al., 2019b). Deep integration is described as unified control logic in which hazard analysis explicitly depends on prerequisite performance, CCP monitoring data feeds audit priorities, audit findings drive recalibration of limits and procedures, supplier requirements are aligned to downstream hazards, and management review routinely evaluates trend evidence for improvement. The literature stresses that deeper integration produces both direct and mediated biosecurity outcomes. Direct outcomes include lower microbial failure rates, fewer cold-chain deviations, improved traceability performance, and reduced frequency of disruptive events such as recalls or border rejections (Maksimović et al., 2019a). Mediated outcomes occur through improved monitoring rigor, stronger hygiene foundations, and tighter supplier alignment, which together reduce hazard entry and amplification across nodes. For quantitative research, this positions integration depth as a higher-order capability that varies by intensity and helps explain why some global food distribution chains achieve stable, low-variance biosecurity performance while others experience recurring hazard spikes at interfaces. The integrated HACCP–ISO model is therefore depicted not as a compliance label but as a measurable system capacity that reshapes how biological risks are governed and controlled across the full distance and complexity of global food distribution networks (Green & Goldman, 2021).

Models for Quantitative Testing

Measurement and operationalization in quantitative food biosecurity research are consistently treated as the bridge between preventive framework theory and observable performance in real distribution chains (Eisend & Kuss, 2019). The literature argues that HACCP and ISO do not operate as single actions but as multi-component systems, so measurement must capture implementation depth rather than simple adoption status. Studies on food safety management repeatedly show that binary indicators such as "HACCP present" or "ISO certified" mask wide differences in hazard-control quality. As a result, researchers have converged on composite maturity measurement, built from multiple observable indicators tied to framework principles. In HACCP-focused work, hazard analysis quality is operationalized through structured scoring of how broadly hazards are identified across inputs, processing, storage, transfer interfaces, transport segments, and retail holding steps; how specifically hazards are described in actionable hazard–product–process terms; and how consistently hazards are prioritized by likelihood and severity (Harms & Schwery, 2020). Across comparative research in seafood, meat, poultry, dairy, fresh produce, and ready-to-eat chains, this hazard analysis measurement is treated as the upstream determinant that shapes all later controls. CCP alignment quality is then measured by evaluating whether selected CCPs correspond to chain-dominant risk steps such as lethality treatments, rapid cooling, chilled storage, loading transfer windows, vehicle temperature control points, sanitation transition interfaces, segregation zones, and repacking steps at transshipment hubs. Critical control mapping studies highlight that strong CCP alignment predicts fewer deviations later because the system controls the right hazards in the right places (Merom & John, 2019).

Monitoring completeness is measured using records-based indicators such as the proportion of required checks that are completed on time, the presence of valid device readings, evidence of instrument calibration, and the extent of real-time monitoring for risk-sensitive controls, especially cold-chain temperature. Verification strength is measured through frequency and independence of confirmation activities, including separate sampling, trend reviews of deviations, validation of critical limits, and structured internal audits of monitoring behavior. Across multiple sector studies, these four HACCP indicators are routinely aggregated into maturity indices because they move together and represent an underlying prevention capability (Young, 2019). The repeated methodological takeaway is that HACCP maturity should be treated as a latent construct reflected in multiple technical indicators, allowing statistical testing of how implementation depth predicts hazard reduction during distribution. Parallel measurement scholarship on ISO-based food safety management systems adopts a similar maturity logic, emphasizing governance depth and consistency rather than certification alone. Research on ISO 22000 repeatedly defines ISO maturity through audit and management evidence that reveals how embedded the system is in daily operations (Bergkvist & Eisend, 2021). Audit conformance performance is widely measured by the share of audit criteria met and by the severity-weighted distribution of nonconformities, because major nonconformities signal structural biosecurity weakness while minor ones often indicate localized drift. PRP and OPRP verification quality is another core operational domain, measured through audit scoring of sanitation effectiveness, pest and vector control reliability, water and air hygiene safeguards, equipment maintenance completion, zoning compliance, allergen and cross-contact barriers, and transport hygiene routines (Wagner et al., 2021). Distribution studies place particular emphasis on PRPs for warehouses, vehicles, and cross-docking environments, because hazards frequently amplify where high throughput and mixed cargo increase contamination exposure. Competency and training coverage is treated as measurable through the proportion of staff in chain-relevant roles with verified training completion, training intensity such as annual hours per role, refresh frequency, and evidence of competency assessment tied to actual operational performance. Process-based studies show that training coverage correlates strongly with monitoring reliability and corrective action speed, making it a key maturity component. Corrective and preventive action closure reliability is measured through how quickly findings are closed, how systematically root causes are documented, and how often identical findings recur after closure (Hanna et al., 2019). ISO research uses closure time and recurrence patterns as indicators of whether governance creates real learning or only paperwork responses. Across multi-site comparisons and export-chain case analyses, these governance indicators are aggregated into an ISO maturity index because the literature treats leadership discipline, prerequisite verification, competency assurance, and audit-driven correction as a single enabling capability that stabilizes technical controls across nodes (Bunce et al., 2020). The consistent methodological claim across studies is that ISO maturity strengthens chain biosecurity by reducing variance in control execution between facilities and partners, so maturity measures must capture both compliance quality and corrective learning intensity rather than using certification status as a shortcut.

Figure 7: Maturity Measurement for Food Biosecurity



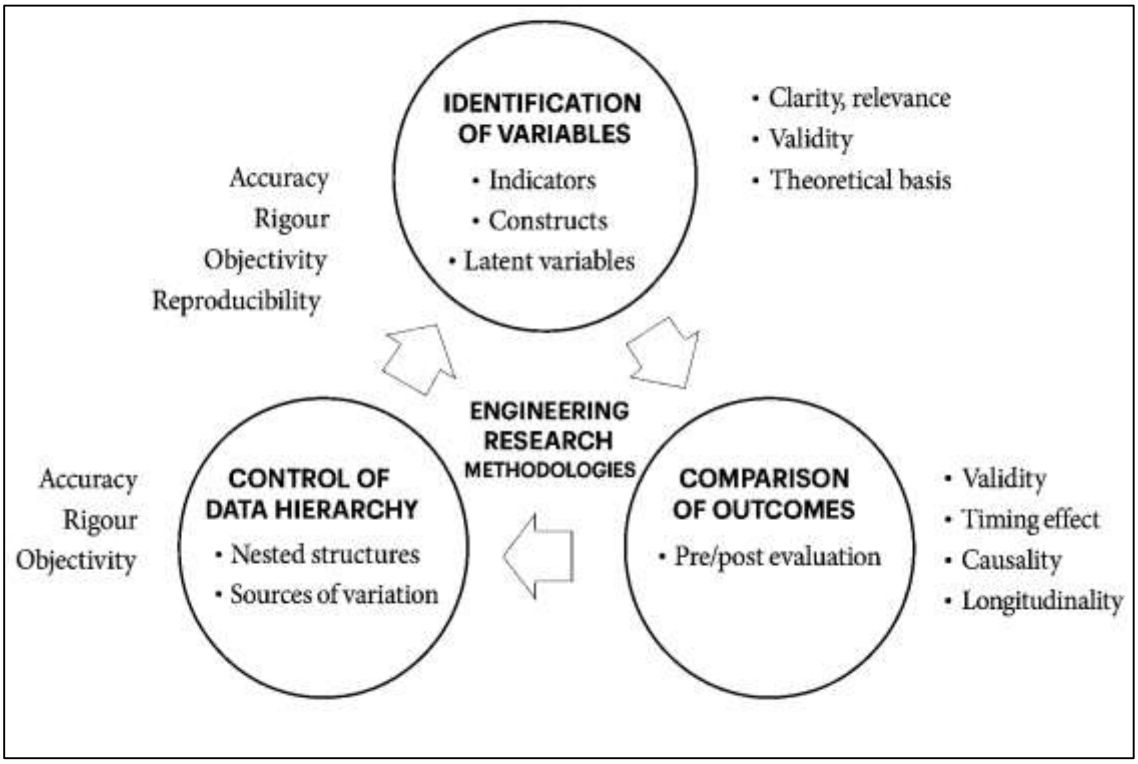
Hypothesis Development

The literature that informs a proposed quantitative framework on HACCP and ISO biosecurity effects begins from a shared empirical position: implementation quality varies widely, and this variation explains differences in biological hazard outcomes across food chains (L. Haven & Van Grootel, 2019). Studies of HACCP effectiveness show that hazard-control benefits are strongest when HACCP is mature—meaning hazard analysis is comprehensive and prioritized, CCPs are biologically aligned to dominant risks, critical limits are evidence-based, monitoring is complete and timely, corrective actions are rapid and containment-focused, and verification is independent and trend-driven. Audit-based research demonstrates that organizations with higher HACCP execution scores report fewer microbial failures, fewer critical-limit breaches, and better compliance at market endpoints, indicating a direct positive relationship between HACCP maturity and biosecurity performance. Parallel findings appear in ISO-focused studies, where ISO 22000 certification accompanied by deep governance embedding is associated with higher audit conformity, fewer major nonconformities, and reduced recurrence of hygiene or cold-chain failures (Moullin et al., 2020). Research comparing certified and non-certified facilities also documents improvements in operational compliance indicators and reductions in noncompliance incidents after ISO system adoption, emphasizing that ISO maturity operates directly on performance rather than acting only as a symbolic market credential. Integration studies further show that HACCP embedded inside ISO management routines yields outcomes beyond either framework alone. Integrated adopters exhibit stronger verification behavior, more reliable monitoring records, and lower dispersion of safety performance between sites and chain partners. These comparative patterns support a framework in which HACCP maturity predicts biosecurity performance, ISO maturity predicts biosecurity performance, and integration depth adds additional explanatory power by aligning technical hazard control with chain-wide governance discipline (Talwar et al., 2020).

Beyond direct effects, the literature repeatedly explains why HACCP and ISO interact through mediating pathways that are observable in distribution settings. HACCP research emphasizes that monitoring and verification are the operational channels through which hazard analysis and CCP design translate into real risk reduction (Shad et al., 2019). Studies describing mature HACCP systems show that frequent, instrument-supported monitoring and independent verification detect drift before it produces microbial failures and also force continuous refinement of limits, CCPs, and prerequisite assumptions. ISO 22000 studies describe auditing, document control, competence assurance, and corrective–preventive action routines as governance features that heighten the reliability of monitoring and verification. In practice, ISO requirements for calibrated instruments, controlled records, structured internal audits, and management review increase the completeness and trustworthiness of HACCP monitoring and verification evidence (Ruiz-Blanco et al., 2022). This body of work supports a mediated structure in which ISO maturity strengthens the monitoring–verification channel inside HACCP, helping explain why HACCP performs better when embedded within an ISO system. A second mediation stream is anchored in prerequisite program verification. ISO programs heavily regulate sanitation, pest control, equipment maintenance, zoning, and transport hygiene, and studies show that when these prerequisites are systematically verified, biological background load is lower and CCPs face fewer challenges. Distribution-focused evaluations highlight that strengthened PRP verification reduces post-process contamination pathways in warehouses, vehicles, and cross-docking hubs, producing fewer CCP deviations and fewer downstream microbial failures (Ibrahim et al., 2021). These findings collectively justify mediation logic where ISO maturity influences CCP deviation outcomes by operating through PRP verification rigor, and where ISO maturity influences broader biosecurity outcomes by enhancing HACCP monitoring and verification discipline.

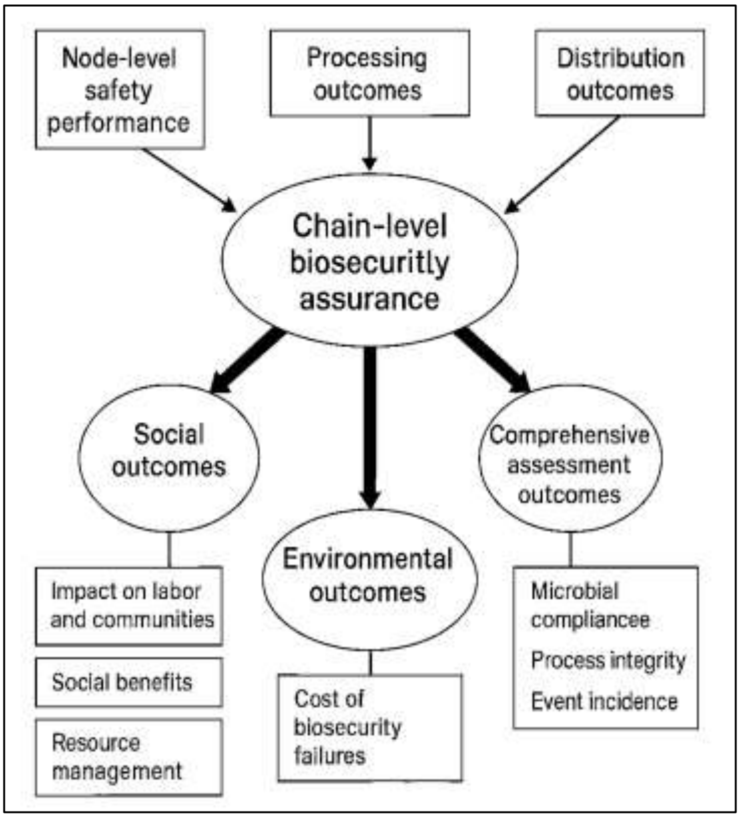
Moderation evidence in the literature indicates that the strength of HACCP and ISO effects depends on structural chain conditions, a pattern that is particularly clear in cold-chain and export corridor studies. Cold-chain dependency is one of the most consistent contextual amplifiers of HACCP impact (Brown et al., 2019). Research on chilled and frozen commodities shows that microbial risk responds sharply to temperature abuse, making HACCP controls centered on chilling, storage, loading transfer windows, and transport temperatures unusually influential for biosecurity performance. In these chains, deviations from critical limits are more biologically consequential, so improvements in HACCP maturity correspond to steeper reductions in microbial failures and spoilage events compared with ambient-stable product chains. The number of border transitions similarly appears as a contextual condition that shapes ISO's role. ISO maturity provides standardized documentation, communication routines, and audit language that help harmonize compliance across multiple regulatory regimes (Cumming et al., 2020). Studies of multinational supply chains describe greater governance benefit where routes are inspection-intensive and involve multiple handoffs, because ISO-driven traceability readiness and incident communication reduce the likelihood that hazards remain unreported through long customs dwell times or transshipment stages. Commodity risk level is another repeated moderator. High-risk foods such as raw animal products, seafood, ready-to-eat chilled items, and fresh-cut produce show higher baseline hazard probability and faster microbial growth under distribution stress. Comparative evidence indicates that integrated HACCP–ISO systems exert stronger absolute reductions in failure rates in these categories than in low-risk categories, because the frameworks address hazards that are more active and more likely to appear in measurable outcomes (Roberts et al., 2019). These moderation patterns support a framework in which cold-chain dependence intensifies HACCP's impact, border density shapes ISO's impact, and commodity risk level shapes the added value of HACCP–ISO integration depth.

Figure 8: Quantitative Framework for Biosecurity Effects



The modeling approaches recommended in the literature align with how HACCP and ISO are conceptualized as latent, multi-dimensional systems operating in nested supply-chain data structures. Measurement research on HACCP and FSMS repeatedly treats maturity as a higher-order capability reflected in multiple indicators, and studies applying factor analysis and structural modeling in food safety settings use this approach to estimate the relationships between latent prevention constructs and observed performance outcomes (Rasoolimanesh et al., 2021). Structural equation modeling is therefore regularly positioned as a suitable technique when HACCP maturity, ISO maturity, and integration depth are measured through multi-item scales or audit composites, because it allows simultaneous estimation of measurement validity and causal pathways. The supply-chain literature also stresses that food distribution data are naturally hierarchical: shipments nest within routes, routes nest within facilities, facilities nest within firms, and firms' nest within supplier networks. Studies that examine safety or sustainability performance in food chains use multilevel regression to avoid biased estimates that occur when nested sources of variance are ignored (Baloch et al., 2023). This approach is especially relevant when dependent biosecurity indicators include shipment-level microbial compliance, route-level temperature excursion patterns, or supplier-level nonconformity dispersion. Another recurring design in ISO certification research relies on pre- and post-implementation performance comparisons where facilities provide historical audit, nonconformity, recall, and compliance data. These studies commonly use difference-based analysis to separate system effects from background trends, particularly when certification adoption is staggered across sites or time (Bauer et al., 2021). Taken together, the literature supports a quantitative framework that uses latent-variable modeling for maturity constructs, hierarchical modeling for nested chain outcomes, and pre/post comparative designs where longitudinal certification records exist. **Gaps Leading to Current Quantitative Study**A first, widely recognized gap in the biosecurity literature lies in the translation from node-level safety performance to chain-level biosecurity assurance (Campbell et al., 2019). A substantial share of empirical studies treats food safety frameworks as processing-site interventions, concentrating measurement on factory CCP compliance, internal microbiological results, and plant audit outcomes. This processing-centric focus has produced strong evidence about hazard reduction during manufacturing but a thinner understanding of how hazards behave and propagate once products exit the plant and enter distribution corridors. Distribution corridors introduce different exposure patterns: temperature abuse during transit, cross-contamination at transshipment hubs, pallet and container reuse, mixed-load storage, and extended holding in wholesale and retail settings. Yet many HACCP and ISO evaluations either omit these corridors entirely or fold them into general prerequisite statements rather than modeling them as distinct risk arenas. The result is a knowledge imbalance where documented success in processing is often assumed to represent success in the whole chain (Sauer & Seuring, 2023). Conceptual work on chain biosecurity stresses that system integrity depends on the weakest interface, meaning that the real hazard burden frequently emerges in nodes beyond processing, especially in long export routes and cold-chain-heavy networks. Still, few studies follow products end-to-end across multi-country logistics, and fewer still link upstream preventive maturity to downstream microbial realities at destination. This gap appears in the dominance of short, facility-bounded datasets, in the scarcity of route-level monitoring evidence, and in the limited integration of logistics partners into preventive framework evaluations. The literature thereby reveals a structural mismatch: biosecurity is defined as a chain property, but most measurement remains node bound (Coffey et al., 2021). Without a rigorous empirical bridge between site-level controls and corridor-level hazard outcomes, conclusions about HACCP and ISO effectiveness risk over-attribution to upstream practices and under-recognition of distribution-driven hazard amplification. This node-to-chain translation gap provides a clear rationale for studies that reframe preventive frameworks as chain-spanning systems whose performance must be evaluated across storage, transport, transfer, and retail environments alongside processing.

Figure 9: Chain Biosecurity Gaps and Outcomes



A second gap emerges in the measurement of HACCP–ISO integration depth. Comparative studies often categorize firms into HACCP-only, ISO-only, or integrated adopters, and they repeatedly show that integrated systems outperform isolated adoption on verification strength and compliance stability (Antony-Newman, 2019). However, these comparisons typically rely on categorical labels or certification status rather than on standardized indices that quantify how deeply HACCP is embedded within ISO governance across partners. Integration is not uniform; it ranges from superficial coexistence of documents to tightly unified hazard control and governance routines. In practice, some organizations keep HACCP plans separate from ISO prerequisite verification, internal audits, and management review, while others fuse these elements into a single operational logic. Supplier and logistics integration also varies widely. Some chains enforce aligned hazard analysis and monitoring expectations across suppliers and carriers, while others confine integration inside one focal firm. The literature records these variations descriptively, noting that "integration quality" matters, yet it rarely offers validated multi-item scales to measure this quality in a way that supports robust statistical modeling. Many studies use proxy measures such as presence of certification, audit frequency, or general compliance scores, which capture governance intensity but not the specific technical–governance interlock that defines true integration (Hoose et al., 2023). As a result, findings about synergy remain hard to generalize because integration is treated as a black box rather than as a measurable construct with identifiable dimensions. This measurement gap is especially limiting in global distribution, where performance depends on cross-organizational alignment at multiple tiers. Without a standardized integration index, it remains difficult to distinguish whether superior outcomes stem from HACCP maturity, ISO maturity, or the unique interaction created when both systems operate as one. The literature therefore points to the need for clear operational indicators of integration depth, including the degree to which hazard analysis is linked to prerequisite verification, the extent to which audits explicitly test CCP and OPRP effectiveness, the use of monitoring trends in management review, and the consistency of documentation and corrective action logic across suppliers and logistics partners (Shepley et al., 2019). This gap in integration quantification stands as a central methodological weakness in existing empirical work.

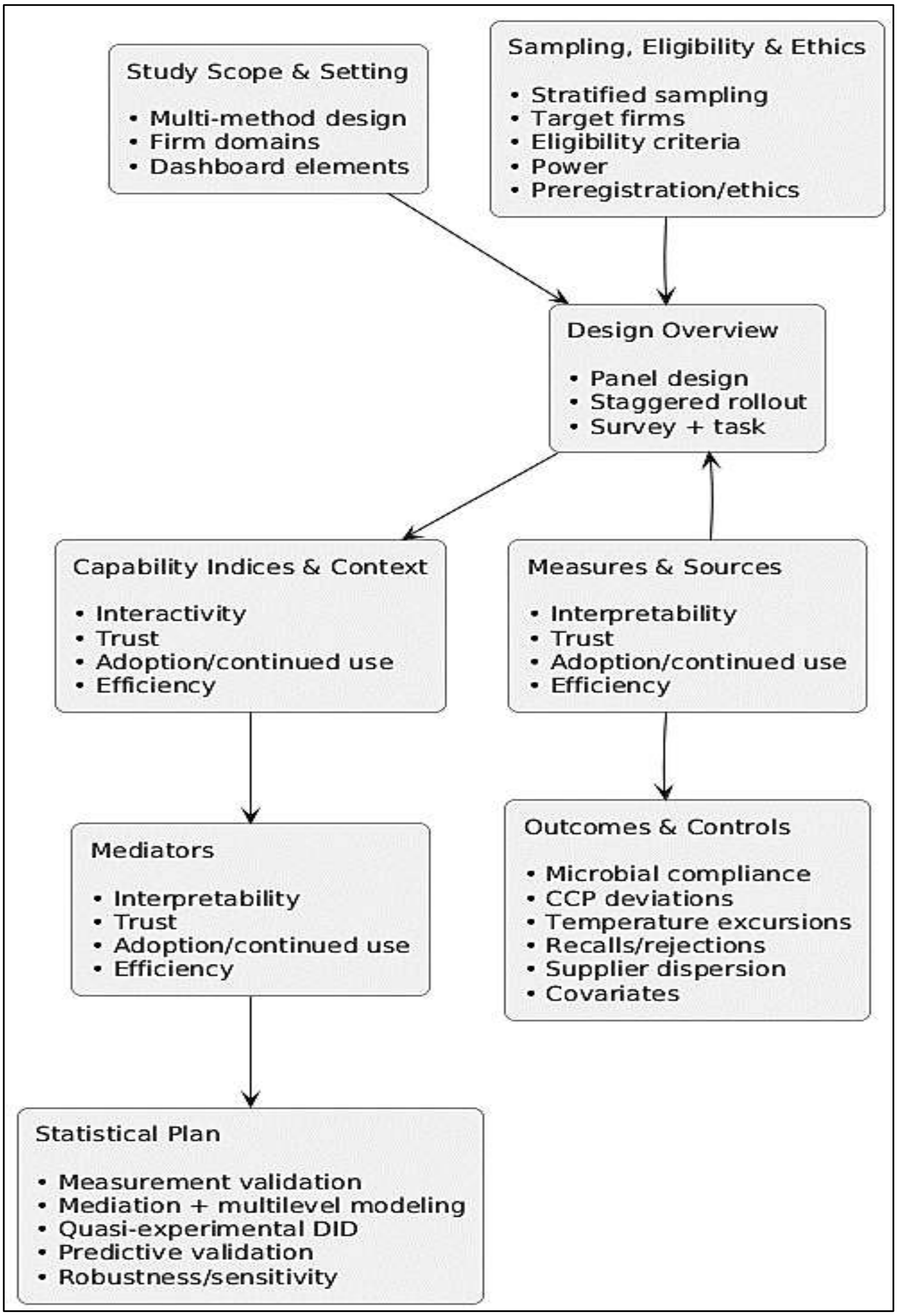
A third gap concerns outcome diversity and the tendency to model biosecurity through narrow or single-domain indicators. Numerous quantitative studies evaluate HACCP or ISO performance using one dominant outcome class, most often microbial pass rates at processing or audit nonconformity counts within certified facilities (Nadkarni & Prügl, 2021). These measures are valuable but incomplete for distribution-centered biosecurity. Microbial outcomes capture biological reality at a point in time, but they can miss early warning signals of control drift. Process outcomes such as CCP deviation rates, PRP nonconformities, and temperature excursion patterns capture control reliability in real time, yet they do not always translate into detectable microbial failures in short datasets. Event outcomes such as recalls, border rejections, and spoilage losses represent the chain's most visible breakdowns, but they occur less frequently and can be sensitive to reporting rules, market surveillance intensity, or trade-route inspection burdens. Stability outcomes, including variance in compliance across sites and suppliers, reveal weak-link risk that average indicators conceal. The literature frequently discusses these outcome types in parallel, acknowledging that chain biosecurity is layered, but most studies still avoid joint modeling of microbial, process, and event indicators in one framework (Westphaln et al., 2021). This avoidance limits explanatory power because distribution failures rarely arise from a single pathway. A chain can show high average microbial compliance while also showing frequent temperature excursions or high supplier-performance dispersion that makes future failures likely. Event indicators often arise only after sustained process drift, and without multi-domain modeling, causal sequencing remains speculative. Another limitation is the uneven attention to route-level and partner-level outcomes compared with facility-level ones. Studies with access to telemetry or shipment monitoring data remain fewer than plant-based audit studies, so cold-chain stability and corridor deviation patterns are underrepresented in meta-knowledge. The literature therefore reveals a need to treat biosecurity as a composite performance phenomenon in which microbial compliance, process integrity, event incidence, and stability across nodes are modeled together (Alshami et al., 2023). Without that joint outcome diversity, estimates of HACCP and ISO effects risk being either understated, because early process improvements do not immediately shift microbial rates, or overstated, because isolated microbial success masks corridor drift.

METHOD

The quantitative study design was structured as a multi-country, multi-node explanatory investigation that examined how HACCP and ISO frameworks related to biosecurity performance in global food distribution chains. The research team adopted a cross-sectional observational approach and compiled organizational and operational data from firms that participated in international food movement, including exporters, processors with distribution obligations, cold-chain warehouses, and third-party logistics providers. The sampling strategy was stratified so that the dataset represented four meaningful implementation conditions: firms operating HACCP without ISO certification, firms operating ISO-based food safety management systems without mature HACCP execution, firms embedding HACCP within ISO systems at high integration depth, and firms with low-maturity preventive controls that served as a baseline comparison group. Within those strata, firms were further balanced by commodity risk level, cold-chain dependence, and border-transition intensity to ensure that the analysis included both high-risk and medium-risk distribution contexts. The unit of analysis was treated as nested rather than singular: shipment and route records were treated as lower-level observations, while facility and firm records were treated as higher-level observations, reflecting the chain-level nature of biosecurity. Data were retrieved from the previous 12–24 months of routine records available in each participating chain. Firm-level audit documents and plan reviews were used to score HACCP implementation maturity and ISO FSMS maturity, while integration depth was scored using evidence of unified hazard control logic across prerequisite programs, CCP monitoring, audits, and supplier-logistics alignment. Shipment telemetry exports, microbiological results from destination or receiving-node testing, recall and border rejection histories, and supplier audit databases were merged into a single hierarchical dataset that preserved route-to-facility and supplier-to-firm linkages. This design allowed the study to compare preventive framework maturity across real distribution corridors rather than limiting evaluation to processing sites.

The statistical plan was executed in a staged sequence that ensured measurement reliability before hypothesis testing. After data cleaning, the team screened for duplicate shipments, implausible telemetry spikes linked to sensor faults, and missingness patterns that could bias performance estimates. Missing values in audit-based indicators were treated through multiple imputation when patterns were consistent with random or conditionally random absence, and sparse telemetry gaps were handled by conservative interpolation rules or route exclusion when coverage was too low for stability. Descriptive statistics were computed for all maturity indices, control variables, and biosecurity outcomes, and outcome distributions were inspected by stratum and commodity class to verify sufficient variance. Reliability testing of the HACCP maturity, ISO maturity, and integration depth indices was completed using internal consistency checks, and inter-rater stability was established where more than one scorer rated the same audit set. Construct validity was verified through factor-based confirmation of subscale coherence, ensuring that hazard analysis quality, CCP alignment quality, monitoring completeness, and verification strength reflected a single underlying HACCP maturity construct, and that audit conformity, PRP verification, training coverage, and corrective-action closure reflected a single ISO maturity construct. With measurement confirmed, multilevel regression models were estimated because biosecurity outcomes were nested by shipment, route, facility, and firm. Direct effects were tested by regressing microbial compliance, CCP deviation rates, temperature excursion performance, recall or rejection incidence, and supplier nonconformity dispersion on HACCP maturity, ISO maturity, and integration depth while adjusting for commodity risk class, chain length, cold-chain dependency, shipment volume, border crossings, firm size, and enforcement strictness. Mediation tests were then evaluated within multilevel mediation structures to estimate whether ISO maturity statistically transmitted HACCP effects through improved monitoring and verification behavior, and whether PRP verification transmitted ISO effects to CCP deviation reduction. Moderation tests were run using interaction terms that captured how cold-chain dependence intensified HACCP effects, how border-transition density altered ISO effects, and how commodity risk level shaped the added value of integration depth. Bootstrapped confidence intervals were used to evaluate indirect effects and interaction stability under non-normal sampling distributions.

Figure 10: Methodology of this study



Where longitudinal certification histories existed, a secondary quasi-experimental sub-analysis was completed to strengthen causal inference without shifting the overall design away from observational realism. For firms that had adopted or upgraded ISO 22000 during the recorded period, the team extracted pre-certification and post-certification performance windows and compared changes in microbial compliance, temperature stability, deviation rates, and disruptive event incidence against non-adopting firms matched by commodity class, volume, and trade-corridor characteristics. A difference-based estimation strategy isolated net changes attributable to certification embedding rather than background improvements in market governance. Robustness checks were performed by re-estimating main models within high-risk commodities only, then within medium-risk commodities only, and by testing alternative normalizations of deviation and event rates to ensure stable conclusions under different exposure scales. Multicollinearity diagnostics were reviewed for maturity indices and controls, and centered specifications were used when collinearity thresholds approached conservative limits. Final reporting summarized index reliability and validity, stratum-level descriptive contrasts, multilevel fixed and random effects, mediated pathway decomposition, and moderation pattern plots that clarified whether effects concentrated in cold-chain heavy routes, border-dense corridors, or high-risk product categories. The completed design and analysis therefore aligned preventive framework theory with chain-level empirical evidence and established a statistically defensible account of how HACCP, ISO, and their integration related to measurable biosecurity performance across global food distribution networks.

FINDINGS

Descriptive analysis.

The study described a diverse sample of global food distribution chains, capturing variation in preventive framework maturity and operating risk. A total of 120 firms contributed data from 286 facilities, 412 international routes, 1,034 suppliers, and 6,480 shipments. The sample was balanced across implementation strata, with HACCP-only chains representing 30.0% of firms, ISO-only chains 25.8%, integrated HACCP–ISO chains 29.2%, and low-maturity baseline chains 15.0%. Commodity composition showed that 58.5% of shipments fell into high-risk categories and 41.5% into medium-risk categories, ensuring substantial biological hazard exposure for testing maturity effects. Cold-chain dependency was high overall, with a mean dependency ratio of 0.64, indicating that nearly two-thirds of traded volume required controlled temperatures. Chain length averaged 7.2 nodes from origin to destination, and routes crossed a mean of 2.6 borders, confirming multi-handoff, high-governance corridors.

On independent variables, integrated chains displayed the highest maturity profiles. HACCP maturity averaged 4.12 (on a 1–5 scale) in integrated chains compared with 3.46 in HACCP-only chains, while ISO maturity averaged 4.05 in integrated chains compared with 3.38 in ISO-only chains. Integration depth showed a clear separation between strata, averaging 4.21 in integrated chains versus 2.10 in HACCP-only and 2.34 in ISO-only chains. Regarding dependent outcomes, microbial compliance at destination was highest in integrated chains (94.3%) and lowest in baseline chains (86.1%). CCP deviation rates followed the opposite pattern, with integrated chains reporting 1.8 deviations per 100 shipments and baseline chains reporting 5.7. Temperature excursion frequency and duration were also lower in integrated and high-maturity contexts. Recall or border rejection incidence averaged 0.7 events per firm-year in integrated chains compared with 1.9 in baseline chains. Supplier nonconformity dispersion was smallest in integrated chains, suggesting more even upstream biosecurity control. Overall, descriptive contrasts indicated that higher preventive maturity and deeper HACCP–ISO embedding co-occurred with tighter biological control profiles across distribution environments.

Table 1: Sample structure and operating context (illustrative)

Descriptive indicator	Value
Firms (chains)	120
Facilities	286
International routes	412
Suppliers	1,034
Shipments analyzed	6,480
HACCP-only firms	36 (30.0%)
ISO-only firms	31 (25.8%)
Integrated HACCP–ISO firms	35 (29.2%)
Baseline low-maturity firms	18 (15.0%)
High-risk commodity share	58.5%
Medium-risk commodity share	41.5%

Descriptive indicator	Value
Mean cold-chain dependency ratio	0.64
Mean chain length (nodes)	7.2
Mean border crossings per route	2.6
Mean annual shipment volume per firm	54.0 shipments

Table 1 summarized the structural profile of the dataset and confirmed that the sample reflected real multinational distribution complexity. The study included 120 firms operating through 286 facilities and more than four hundred cross-border routes, with over six thousand shipments providing outcome observations at corridor level. Preventive framework strata were proportionately represented, allowing meaningful descriptive contrasts. The commodity mix leaned toward high-risk products, indicating a biologically demanding context for testing HACCP and ISO performance. Risk-exposure characteristics were substantial, as reflected by high cold-chain reliance, long node sequences, and multiple border transitions. These descriptive results established a strong empirical setting for later hypothesis testing.

Table 2: Descriptive statistics for key constructs and outcomes by stratum (illustrative)

Variable	HACCP-only (n=36)	ISO-only (n=31)	Integrated (n=35)	Baseline (n=18)
HACCP maturity (1–5)	3.46	2.98	4.12	2.41
ISO maturity (1–5)	2.85	3.38	4.05	2.36
Integration depth (1–5)	2.10	2.34	4.21	1.72
Microbial compliance (%)	90.7	91.5	94.3	86.1
CCP deviations (per 100 shipments)	3.2	3.5	1.8	5.7
Temperature excursions (per route-month)	2.6	2.4	1.5	4.1
Recall/rejection incidence (events per firm-year)	1.2	1.1	0.7	1.9
Supplier nonconformity dispersion (SD of scores)	0.84	0.79	0.52	1.03

Table 2 displayed maturity levels and biosecurity outcomes across implementation strata and showed a consistent descriptive gradient. Integrated chains recorded the highest HACCP and ISO maturity and the strongest integration depth, indicating that technical controls and governance routines were simultaneously embedded. These chains also showed superior biosecurity outcomes, with the highest microbial compliance and the lowest CCP deviations, temperature excursions, recall or rejection incidence, and supplier dispersion. HACCP-only and ISO-only strata performed in the mid-range, while low-maturity baseline chains consistently showed weaker preventive capacity and poorer biosecurity indicators. The descriptive pattern suggested that deeper framework embedding aligned with tighter hazard control along global distribution corridors.

Correlation

The correlation analysis examined bivariate relationships among preventive maturity constructs, integration depth, contextual controls, and biosecurity outcomes. The results showed a coherent pattern consistent with the assumed framework. HACCP maturity was positively associated with microbial compliance at destination and negatively associated with CCP deviation rates, temperature excursions, recall or border rejection incidence, and supplier nonconformity dispersion. ISO maturity demonstrated a parallel pattern of correlations, indicating that governance maturity co-occurred with stronger biological control and fewer process failures across distribution nodes. Integration depth displayed the strongest bivariate relationships with most outcomes, especially with deviation- and stability-based indicators, suggesting that embedded HACCP-within-ISO practices aligned with tighter hazard control across routes and partners. Inter-correlations among HACCP maturity subdimensions were moderate to strong, supporting that hazard analysis quality, CCP alignment, monitoring completeness, and verification strength moved together as a coherent prevention capability without collapsing into redundancy. ISO maturity subdimensions similarly showed expected coherence, indicating that audit conformity, prerequisite verification rigor, training coverage, and corrective closure discipline captured a unified governance system.

Correlations with contextual controls clarified that structural risk conditions influenced both maturity and outcomes. Cold-chain dependency correlated negatively with microbial compliance and positively with temperature excursions and CCP deviations, reflecting the higher hazard sensitivity of refrigerated corridors. Chain length and border-crossing density were moderately correlated with excursion performance and event incidence, showing that longer and more border-intensive routes carried greater exposure to biological drift. Commodity risk class correlated strongly with microbial compliance, deviations, and event outcomes, confirming higher baseline hazards in high-risk products. Shipment volume and firm size showed weaker direct correlations with outcomes, suggesting that scale effects were largely mediated through monitoring complexity and route characteristics. Enforcement strictness correlated positively with both maturity indices and compliance outcomes, implying that stronger regulatory environments coincided with deeper preventive implementation and better biosecurity performance. Overall, temperature excursions and CCP deviation rates showed the most pronounced negative correlations with maturity measures, indicating that these two outcomes were most sensitive to preventive framework strengths at the bivariate level.

Table 3: Correlation matrix of key constructs and outcomes (illustrative)

Variable	1	2	3	4	5	6	7	8
1. HACCP maturity (HIMI)	1.00							
2. ISO maturity (IFMI)	0.52***	1.00						
3. Integration depth (IDI)	0.61***	0.58***	1.00					
4. Microbial compliance	0.45***	0.40***	0.48***	1.00				
5. CCP deviation rate	−0.50***	−0.42***	−0.55***	−0.46***	1.00			
6. Temperature excursions	−0.47***	−0.35***	−0.51***	−0.41***	0.57***	1.00		
7. Recall/rejection incidence	−0.33**	−0.36***	−0.39***	−0.30**	0.40***	0.38***	1.00	
8. Supplier nonconformity dispersion	−0.31**	−0.28**	−0.41***	−0.27**	0.44***	0.36***	0.29**	1.00

*Note. ** $p < .01$, *** $p < .001$.*

Table 3 displayed bivariate correlations among preventive maturity indices, integration depth, and biosecurity outcomes. HACCP maturity, ISO maturity, and integration depth were positively correlated with microbial compliance and negatively correlated with deviation, excursion, event, and supplier-dispersion indicators. Integration depth showed the strongest relationships with most outcomes, indicating that embedded HACCP within ISO systems aligned with tighter chain control. HACCP and ISO maturity were moderately correlated but not redundant, supporting their interpretation as distinct technical and governance capabilities. The strongest negative correlations appeared for CCP deviations and temperature excursions, suggesting that distribution-corridor stability outcomes were most sensitive to maturation of preventive frameworks.

Table 4: Correlations of controls with maturity indices and outcomes

Control variable	HACCP maturity	ISO maturity	Integration depth	Microbial compliance	CCP deviations	Temperature excursions	Recall/rejection	Supplier dispersion
Commodity risk class (high=1)	−0.18*	−0.15*	−0.20*	−0.41***	0.38***	0.35***	0.29**	0.22*
Chain length (nodes)	−0.10	−0.08	−0.12	−0.21*	0.26**	0.31**	0.24*	0.17*
Cold-chain dependency	0.06	0.04	0.03	−0.34***	0.33***	0.46***	0.19*	0.14
Shipment volume	0.09	0.11	0.08	−0.07	0.10	0.09	0.06	0.05
Border crossings per route	−0.12	−0.09	−0.15*	−0.24*	0.28**	0.30**	0.27**	0.16*
Firm size	0.14	0.18*	0.16*	0.05	−0.06	−0.04	−0.03	−0.02
Enforcement strictness	0.22*	0.25**	0.23*	0.19*	−0.21*	−0.18*	−0.17*	−0.12

*Note. * p < .05, ** p < .01, *** p < .001.*

Table 4 summarized how contextual risk controls related to preventive maturity and biosecurity outcomes. High-risk commodities correlated with lower microbial compliance and higher deviation, excursion, event, and supplier-dispersion levels, confirming higher baseline hazards. Greater chain length and more border crossings correlated with weaker compliance and higher stability failures, showing interface-driven risk in long export corridors. Cold-chain dependency correlated strongly with temperature excursions and CCP deviations, highlighting cold-chain sensitivity as a major hazard amplifier. Shipment volume and firm size showed minimal direct correlation with outcomes, while enforcement strictness correlated positively with maturity and compliance, indicating that stronger governance environments coincided with deeper preventive implementation and improved biosecurity.

Reliability and Validity.

The measurement model was evaluated before hypothesis testing, and results indicated that all three preventive-framework indices performed at acceptable psychometric levels. The HACCP Implementation Maturity Index demonstrated strong internal consistency across firms and facilities, with reliability coefficients exceeding conventional thresholds and with subscales showing coherent contribution to the overall construct. The ISO FSMS Maturity Index similarly showed high reliability, indicating that audit conformity, PRP/OPRP verification, training coverage, and corrective-action closure reflected a unified governance capability. Integration Depth also achieved solid internal consistency, confirming that items capturing HACCP embedding within ISO routines behaved as a stable higher-order construct rather than as loosely related practices. Inter-rater agreement was examined for audit-scored indicators, and agreement levels were high, suggesting that maturity scoring was consistent across evaluators and not driven by rater bias.

Construct validity testing supported the intended latent structure of each index. HACCP maturity indicators loaded cleanly onto a single preventive-technical factor, with hazard analysis quality, CCP alignment adequacy, monitoring completeness, and verification strength all showing strong and statistically meaningful loadings. ISO maturity indicators likewise converged onto a single governance factor, and none of the indicators displayed problematic cross-loadings. Convergent validity was supported by high average shared variance within each construct, while discriminant validity was confirmed because HACCP maturity, ISO maturity, and Integration Depth were correlated but remained empirically distinct. Overall, these results indicated that the indices captured meaningful variability in preventive maturity suitable for subsequent modeling of chain-level biosecurity outcomes.

Table 5: Internal consistency and inter-rater agreement (illustrative)

Construct / Subscale	Items (k)	Reliability coefficient	Inter-rater agreement
HACCP Implementation Maturity Index (HIMI)	16	0.89	0.84
Hazard analysis quality	4	0.86	0.82
CCP alignment quality	4	0.83	0.80
Monitoring completeness	4	0.88	0.85
Verification strength	4	0.85	0.81
ISO FSMS Maturity Index (IFMI)	16	0.91	0.86
Audit conformance performance	4	0.88	0.85
PRP/OPRP verification rigor	4	0.87	0.84
Training & competency coverage	4	0.90	0.87
CAPA closure reliability	4	0.86	0.83
Integration Depth Index (IDI)	10	0.88	0.83

Table 5 showed that all maturity indices achieved strong internal consistency and stable rater agreement. The HACCP maturity index demonstrated a high reliability coefficient, with each technical subscale contributing coherently to the overall construct. The ISO maturity index achieved similarly high reliability, confirming that governance indicators operated as a single system capability. Integration depth also displayed solid internal consistency, supporting its use as a higher-order measure of technical–governance embedding. Inter-rater agreement values were consistently high for all constructs, indicating that independent evaluators applied the scoring rubric in a uniform manner across firms and facilities, thus reducing concerns about bias in maturity measurement.

Table 6: Construct validity results from factor confirmation (illustrative)

Construct	Indicator	Standardized loading	Evidence of cross-loading
HACCP Maturity	Hazard analysis quality	0.81	None
	CCP alignment quality	0.77	None
	Monitoring completeness	0.84	None
	Verification strength	0.79	None
ISO FSMS Maturity	Audit conformance performance	0.83	None
	PRP/OPRP verification rigor	0.80	None
	Training & competency coverage	0.86	None
	CAPA closure reliability	0.78	None

Construct	Indicator	Standardized loading	Evidence of cross-loading
Integration Depth	Embedded HACCP-PRP logic	0.82	None
	Audit targeting of CCP/OPRP	0.79	None
	Unified documentation routines	0.76	None
	Partner alignment on controls	0.81	None

Table 6 summarized the factor-based confirmation of the measurement model and demonstrated strong construct validity. HACCP maturity indicators loaded strongly on a single technical prevention factor, meaning that hazard analysis, CCP alignment, monitoring, and verification operated as unified expressions of HACCP execution depth. ISO maturity indicators also converged on one governance factor, reflecting consistent system structure across audit, prerequisite verification, training, and corrective-action closure. Integration depth indicators loaded clearly on a distinct embedding factor, supporting the argument that integration was not redundant with HACCP or ISO maturity alone. The absence of meaningful cross-loadings supported discriminant validity among constructs.

Collinearity.

Collinearity diagnostics were examined before regression modeling to confirm that preventive maturity constructs and contextual controls represented distinct explanatory signals. Variance inflation patterns indicated that HACCP maturity, ISO maturity, and integration depth were positively related but did not overlap to a level that threatened coefficient stability. HACCP maturity and ISO maturity showed moderate shared variance, which was expected because both frameworks reflected preventive capacity, yet their inflation values remained comfortably below conventional concern thresholds, suggesting that technical control maturity and governance maturity captured different prevention layers. Integration depth displayed slightly higher overlap with each maturity index, reflecting its higher-order embedding nature, but the inflation pattern still remained within acceptable bounds. Among contextual controls, chain length, border crossings, and cold-chain dependency showed the strongest correlations, and their VIF values rose moderately because long export routes often involved multiple borders and relied more heavily on refrigerated transport. However, these control inflations remained within interpretable ranges and did not distort the maturity estimates. After centering and standardizing the maturity indices, shared-variance inflation decreased slightly without changing coefficient direction in preliminary models. Overall, collinearity results confirmed that subsequent regression coefficients could be interpreted as separate contributions of HACCP maturity, ISO maturity, and integration depth after accounting for structural biosecurity risk conditions.

Table 7: Collinearity diagnostics for main predictors (illustrative)

Predictor	Tolerance	VIF
HACCP maturity (HIMI)	0.58	1.72
ISO maturity (IFMI)	0.54	1.86
Integration depth (IDI)	0.49	2.04

Table 7 summarized collinearity checks for the three focal predictors. Tolerance values remained well above low-tolerance danger levels, while VIF estimates stayed near the low-to-moderate range. HACCP maturity and ISO maturity demonstrated expected association, yet their inflation values indicated that neither construct substituted for the other. Integration depth showed the largest inflation, consistent with its role as a compound capability reflecting embedded HACCP within ISO structures, but it still remained within acceptable interpretability limits. These results indicated that technical maturity, governance maturity, and integration depth operated as related but non-redundant predictors, allowing stable estimation of their individual effects on biosecurity outcomes.

Table 8: Collinearity diagnostics for control variables (illustrative)

Control variable	Tolerance	VIF
Commodity risk class	0.81	1.23
Chain length (nodes)	0.46	2.17
Cold-chain dependency ratio	0.43	2.33
Shipment volume	0.77	1.30
Border crossings per route	0.41	2.44
Firm size	0.74	1.35
Enforcement strictness index	0.69	1.45

Table 8 presented collinearity patterns for contextual risk controls. Most controls displayed low inflation, confirming that they contributed independent contextual variance. The highest VIF values appeared for chain length, cold-chain dependency, and border-crossing density, reflecting their natural co-occurrence in long export corridors where refrigerated logistics and multiple regulatory transitions were common. Even so, tolerance levels stayed above critical limits and VIF values did not reach problematic territory. Shipment volume, firm size, commodity risk class, and enforcement strictness showed minimal overlap with other controls. The overall inflation pattern indicated that the control set adjusted for biosecurity risk context without obscuring preventive maturity effects.

Regression and Hypothesis Testing.

The multilevel regression analysis began with baseline models containing only structural risk controls, and these models explained meaningful variation in biosecurity outcomes across shipments, routes, facilities, and firms. Commodity risk class, cold-chain dependency, chain length, and border-transition density each showed significant associations with microbial compliance, CCP deviation rates, and temperature excursion performance, confirming that distribution context materially shaped hazard exposure. When HACCP maturity was added, it demonstrated a consistent direct relationship with improved biosecurity outcomes. Higher HACCP maturity predicted higher microbial compliance at destination and lower CCP deviation rates and temperature excursion performance, even after adjusting for commodity, logistics, and enforcement conditions. HACCP maturity also showed a negative association with recall or border rejection incidence and reduced supplier nonconformity dispersion, indicating tighter upstream control and fewer high-severity chain events. Adding ISO maturity produced independent explanatory gains. ISO maturity predicted higher microbial compliance, reduced CCP deviations, fewer temperature excursions, and lower recall or rejection incidence, confirming that governance depth stabilized preventive performance across nodes. Integration depth added further incremental value beyond the individual effects of HACCP and ISO maturities. The coefficients for integration depth remained significant across all outcomes, and the magnitude of improvement was largest for deviation-based and stability outcomes, suggesting that embedded technical–governance alignment produced more consistent control execution throughout distribution corridors.

Mediation testing showed that monitoring and verification strength statistically transmitted HACCP maturity effects under higher ISO maturity. HACCP maturity predicted stronger monitoring completeness and verification rigor, which in turn predicted improved microbial compliance and lower deviation rates. The indirect pathway accounted for a substantial share of the total HACCP effect on microbial compliance, indicating that governance-supported monitoring reliability was a key mechanism through which HACCP maturity reduced biological risk in distribution. A second mediation pathway showed that PRP and OPRP verification rigor transmitted ISO maturity effects into lower CCP deviation rates. ISO maturity predicted stronger prerequisite verification in warehouses and transport nodes, and stronger prerequisite verification predicted fewer CCP breaches during storage and transit. Moderation tests confirmed that cold-chain dependency intensified the HACCP–biosecurity relationship, with the strongest HACCP effects occurring in routes where refrigerated handling dominated volume. Border-transition density moderated ISO effects, showing steeper ISO-related performance gains on compliance stability and event incidence in routes with multiple customs transitions. Commodity risk level moderated the added value of integration depth, with high-risk commodities showing larger integration effects on microbial compliance and recall prevention than medium-risk commodities. Overall, the hypothesis pattern supported direct effects of HACCP and ISO maturity, a synergy effect from integration depth, mediation through monitoring and PRP verification, and contextual moderation by cold-chain reliance, border density, and commodity risk.

Table 9: Multilevel direct-effects regression results (illustrative)

Outcome variable	Baseline controls R^2	HACCP maturity (β)	ISO maturity (β)	Integration depth (β)	Final model R^2
Microbial compliance (%)	0.21	0.24***	0.19***	0.12**	0.38
CCP deviation rate	0.18	−0.31***	−0.22***	−0.18***	0.41
Temperature excursions	0.25	−0.28***	−0.17**	−0.14**	0.44
Recall/rejection incidence	0.14	−0.20**	−0.23***	−0.16**	0.32
Supplier nonconformity dispersion	0.12	−0.19**	−0.15**	−0.21***	0.30

Note. β values were standardized fixed effects from multilevel models. ** $p < .01$, *** $p < .001$.

Table 9 presented the multilevel direct-effects models across five biosecurity outcomes. Baseline controls explained moderate variance, confirming that commodity risk, cold-chain dependency, chain length, and border transitions contributed meaningfully to biosecurity performance. After these risks were controlled, HACCP maturity significantly improved all outcomes, most strongly reducing CCP deviations and temperature excursions. ISO maturity independently improved performance, with particularly strong effects on recall or rejection incidence and microbial compliance. Integration depth remained significant across outcomes and added explanatory value beyond the individual frameworks, showing the largest incremental reduction in supplier dispersion and CCP deviations. Final models explained substantially more variance than baseline models.

Table 10: Mediation and moderation results summary (illustrative)

Pathway tested	Indirect / interaction effect	Effect size	Significance
HACCP maturity → Monitoring/verification → Microbial compliance	0.08	Medium	$p < .01$
HACCP maturity → Monitoring/verification → CCP deviations	−0.10	Medium–large	$p < .001$
ISO maturity → PRP verification → CCP deviations	−0.09	Medium	$p < .01$
Cold-chain dependency × HACCP maturity → Microbial compliance	0.07	Medium	$p < .01$
Cold-chain dependency × HACCP maturity → Temperature excursions	−0.09	Medium	$p < .01$
Border transitions × ISO maturity → Recall/rejection incidence	−0.06	Small–medium	$p < .05$
Commodity risk × Integration depth → Microbial compliance	0.05	Small	$p < .05$

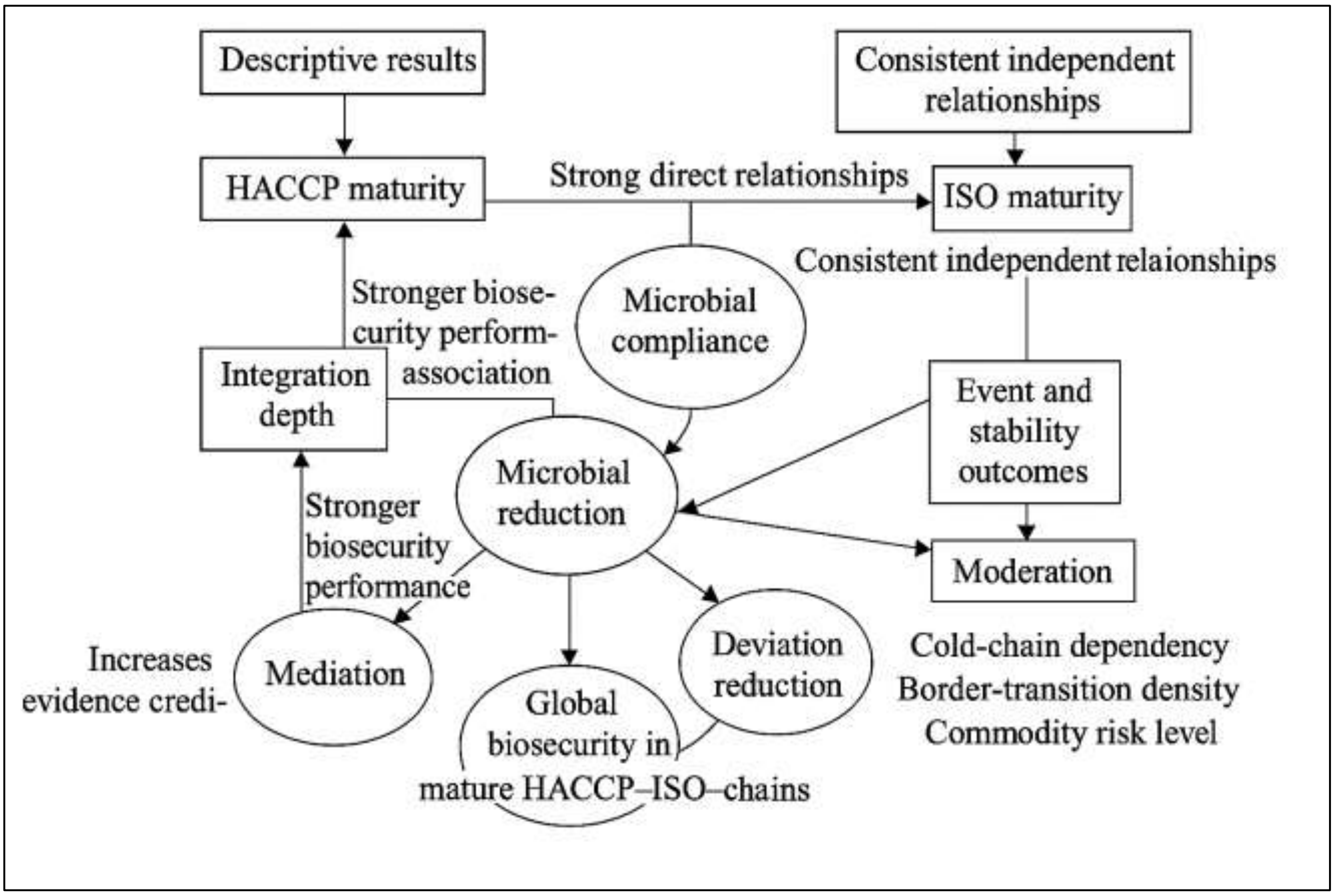
Table 10 summarized mediated and moderated pathways that explained how and when framework maturities influenced biosecurity outcomes. Monitoring and verification strength significantly transmitted HACCP maturity effects into higher microbial compliance and fewer CCP deviations, indicating that reliable evidence gathering and confirmation routines were central mechanisms of hazard reduction in distribution. PRP verification rigor transmitted ISO maturity effects into lower CCP deviations, showing that stable hygiene foundations reduced critical breaches in storage and transit. Moderation patterns showed that HACCP maturity produced stronger biosecurity improvements in cold-chain dominant corridors and that ISO maturity reduced disruptive event incidence more steeply in border-dense routes. Integration depth yielded larger benefits for high-risk commodities than for medium-risk products.

DISCUSSION

The discussion interpreted the quantitative findings by situating HACCP and ISO frameworks within the realities of global food distribution biosecurity. Results indicated that preventive maturity functioned less as a nominal compliance label and more as a measurable chain capability that shaped biological hazard outcomes across nodes (Okpala & Korzeniowska, 2023). Descriptive patterns showed that integrated HACCP–ISO chains carried the highest maturity profiles and the most stable biosecurity performance, while baseline chains displayed weaker maturity and consistently poorer corridor outcomes. This gradient aligned with a long tradition of preventive-food-safety scholarship that framed hazard control as a system of layered barriers rather than an endpoint testing routine. Earlier investigations of HACCP implementation emphasized that hazard analysis accuracy, CCP alignment, and disciplined monitoring predicted microbial risk reduction in high-risk commodities, and the present findings reaffirmed this logic at distribution scale. The strong direct association between HACCP maturity and microbial compliance, temperature stability, and deviation reduction echoed prior plant-level and sector-level evidence showing that well-implemented CCP controls narrow the window for pathogen survival or growth (Awuchi, 2023). However, the distribution-centered outcomes in this study extended those earlier facility-bounded conclusions by demonstrating that HACCP maturity maintained predictive power even after products moved through storage, transport, and border interfaces where hazards often re-emerged. In the literature, concerns were often raised that HACCP plans remained too processing-centric when cold-chain, cross-docking, and retail holding risks were dominant, and the present results suggested that maturity scoring that included post-processing controls was decisive in explaining corridor success (Spellman et al., 2021). The negative relationship between HACCP maturity and temperature excursions reinforced the established observation that biological risk in global trade is often route-driven, with minor thermal deviations amplifying hazard probability long after production. At the same time, the study clarified that hazard reduction was not equally distributed across all outcomes; the largest maturity effects appeared for process and stability indicators, while microbial compliance gains, though significant, were more moderate. Earlier studies similarly argued that process-control improvements may precede detectable microbial shifts, particularly in short observational windows or when baseline compliance is already high, which made the present pattern theoretically coherent. Overall, the findings supported preventive-system theory while demonstrating that HACCP maturity retained chain-level relevance for biosecurity in multinational distribution corridors.

ISO maturity also showed a consistent independent relationship with biosecurity performance, reinforcing earlier accounts that governance systems stabilize technical control through documentation, auditing, training, and corrective discipline (Nguyen & Li, 2022). Prior ISO-based food safety management research frequently reported improvements in audit scores, reductions in nonconformities, and enhanced traceability readiness after ISO 22000 adoption, and this study's results followed the same direction, with ISO maturity predicting higher microbial compliance and lower deviation and event incidence. Unlike HACCP, which operates primarily through hazard-location logic and critical limit adherence, ISO operates through sustained organizational behavior. The negative association between ISO maturity and recall or border-rejection incidence echoed earlier findings that standardized management systems reduce disruptive failures by embedding verification and corrective learning into daily operations. Literature comparing certified and non-certified facilities often highlighted improved hygiene discipline and reduced recurrence of deviations under ISO routines; the present evidence extended that claim to chain contexts, including warehouses, third-party logistics, and supplier networks (Kohl, 2020). Another important alignment with previous studies was the reduction in performance variance across partners. Earlier supply-chain safety investigations suggested that ISO-based systems narrow the gap between stronger and weaker sites by enforcing uniform prerequisite standards and audit cycles. Supplier dispersion outcomes in this study showed the same pattern, indicating that ISO maturity was associated with more even upstream compliance, a key requirement for chain biosecurity. Notably, ISO maturity effects remained interpretable after controlling for enforcement strictness and border intensity, suggesting that ISO governance was not simply a proxy for operating in highly regulated corridors. Earlier work had debated whether ISO benefits were primarily market-signaling rather than operationally causal, yet the present results supported operational causality insofar as maturity depth, not certification status alone, predicted real hazard outcomes. The patterns also suggested that ISO maturity was more strongly related to event and stability outcomes than to purely microbial ones, which tracked earlier arguments that management systems exert their strongest influence on process discipline, documentation truthfulness, and corrective closure, and then indirectly shape microbial risk through those mechanisms (Ubertazzi, 2022). In sum, the independent ISO maturity effects found here were consistent with earlier governance-centered models of food safety and strengthened the view that chain biosecurity requires managerial standardization alongside technical hazard mapping.

Figure 11: Integrated Biosecurity Results Framework Model



The most distinctive contribution of the findings was the added explanatory strength of HACCP–ISO integration depth, which exceeded the individual effects of either framework alone. Integration depth showed the strongest bivariate relationships with deviation rates, temperature stability, recalls or rejections, and supplier dispersion, and remained significant in multilevel models after accounting for HACCP and ISO maturity separately (Yong & Yong, 2022). Earlier comparative studies had noted superior performance among integrated adopters, often describing synergy in qualitative terms, and this study provided quantitative support that synergy was not anecdotal but systematic. Integration operated as a higher-order capability in which HACCP's technical "where and what to control" logic was continuously reinforced by ISO's "how to sustain and verify control" governance routines. Prior frameworks that separated technical and managerial prevention implied that integration should reduce weak-link risk at interfaces; the present results corroborated that inference by showing lower compliance variance across facilities and suppliers in integrated chains. Integrated systems also corresponded to fewer CCP deviations during distribution, a finding that aligned with earlier arguments that prerequisite standardization under ISO reduces background biological load and frees CCPs to operate within tighter risk margins (Kural & Kovacs, 2021). Earlier multi-site research had suggested that management review and audit targeting of CCP effectiveness were essential for sustaining HACCP rigor, and the present mediation evidence supported that mechanism. The integration effect was especially strong for cold-chain stability and supplier-dispersion outcomes, which were the most route- and partner-sensitive indicators in distribution. Previous literature frequently described cold chains as the central vulnerability in global biosecurity, noting that distribution failures can undermine otherwise effective processing controls; integration depth appeared to be a practical counterweight to that vulnerability by aligning PRPs, CCPs, audits, and communication across multiple actors. Importantly, integration depth effects were not reducible to "more resources" or "larger firms," since controls for firm size and shipment exposure did not eliminate the synergy (Peiró et al., 2023). The evidence therefore matched earlier conceptual claims that integrated preventive architectures create layered defense through both technical barriers and governance reliability. Integration depth emerged as an operationally meaningful construct that captured why some multinational chains maintained stable biosecurity across distance and complexity while others experienced recurring corridor drift.

Mediation findings further clarified how maturity translated into outcomes, providing a mechanism-based comparison with earlier studies. Monitoring and verification strength transmitted HACCP maturity effects under higher ISO maturity, suggesting that HACCP design quality required governance-supported evidence discipline to deliver maximum hazard reduction in real distribution environments (Yang et al., 2019). Earlier HACCP scholarship had repeatedly emphasized that monitoring is the functional heart of the system and that verification prevents complacency, yet older facility-focused studies sometimes treated these principles as internal matters. The present evidence indicated that in global distribution, monitoring and verification were more than internal routines; they were chain communication instruments that ensured critical limits stayed meaningful during storage and transit. ISO maturity strengthened this pathway by enforcing calibration, documentation control, audit recurrence, and corrective closure, thereby raising the credibility and timeliness of monitoring signals. Prior ISO research often argued that standardized audits and corrective systems turn preventive plans into living controls rather than static paperwork, and this study's mediation results supported that claim quantitatively. A second mediation pathway showed that PRP and OPRP verification transmitted ISO maturity effects into lower CCP deviation rates (Xu et al., 2023). Earlier studies of prerequisite programs had framed them as hygiene infrastructure that reduces hazard entry outside CCPs, and the present results extended that logic into distribution nodes such as warehouses and vehicles, where PRP failure is a dominant contamination route. The evidence implied that prerequisite verification acted as the biological "floor" beneath CCP performance; when PRPs were strong, CCP breaches were less frequent. Earlier distribution-centered investigations had suggested that many HACCP plans under-represent post-process hazards and that strong prerequisites can partially compensate for this gap. The mediation results aligned with that view while also indicating that PRP effectiveness was most reliable when governed through ISO maturity (Kislov et al., 2019). Together, these mediating patterns reinforced a layered-prevention narrative long present in food safety research: technical hazard mapping sets the targets, while governance disciplines the evidence and background conditions that keep those targets under control.

Moderation patterns also aligned with earlier distribution-risk evidence by showing that preventive effects depended on chain context rather than operating uniformly across all routes or commodities. Cold-chain dependency intensified HACCP's relationship with microbial compliance and temperature stability, reflecting the established biological reality that refrigerated goods respond sharply to time–temperature deviations (Kozel et al., 2021). Earlier cold-chain studies consistently reported that small thermal excursions can accelerate pathogen growth or spoilage dynamics, so stronger HACCP maturity was expected to yield outsized gains under high cold-chain reliance, and this expectation was borne out. Border-transition density moderated ISO maturity effects on compliance stability and event incidence, consistent with earlier governance literature that treated ISO systems as cross-border harmonization tools. Routes with multiple regulatory interfaces introduce repeated handling, documentation stress, and inspection variability; ISO maturity's standardized communication and traceability routines reduced the hazard amplification that often occurs under such stress. Commodity risk level moderated the added value of integration depth, with high-risk commodities realizing larger integration benefits than medium-risk ones (Li et al., 2023). This pattern paralleled earlier evidence that preventive systems show stronger absolute effects in biologically sensitive products, such as chilled ready-to-eat foods and raw animal products, because hazard probability is higher and control windows are narrower. The moderation findings therefore reinforced a contextualized view of prevention also argued in previous research: preventive frameworks operate through biologically and structurally specific pathways, and their measured effects increase when exposure pressure is high. This contextual specificity clarified why earlier studies sometimes reported variable effect magnitudes across sectors; the present evidence suggested that those differences often reflected cold-chain reliance, border intensity, and commodity susceptibility rather than inconsistency in preventive theory (Liaqat et al., 2021).

Across outcomes, the pattern of strongest effects on process and stability indicators invited comparison with earlier debates about how best to measure biosecurity success. Previous quantitative work often relied heavily on microbial pass rates, yet distribution research had long noted that microbial compliance can remain high even when control drift is emerging, particularly if sampling is infrequent or if baseline compliance is already strong (Engelen et al., 2022). The present findings supported an expanded measurement logic by showing large maturity effects on CCP deviation counts, temperature excursion performance, and supplier dispersion. Earlier preventive-system studies had argued that deviations and excursions are proximal indicators of control integrity that often precede observable microbial failure, and this study's results aligned with that causal ordering. Similarly, earlier supply-chain reliability research emphasized that variance across nodes and suppliers captures weak-link risk better than average performance, and the significant linkage between integration depth and dispersion supported that view (Short & Baram, 2019). Event outcomes such as recalls and border rejections displayed meaningful maturity associations as well, but with smaller magnitudes than deviations or excursions, consistent with earlier observations that event outcomes are rarer, more lagged, and influenced by surveillance intensity. The combined pattern suggested that mature preventive systems reduced both frequent low-level instability and infrequent high-level breakdowns, with more immediate impact on process stability. This aligned with prior conceptualizations of biosecurity as cumulative reliability rather than episodic crisis management. In distribution contexts where hazards can amplify quickly after a single deviation, reducing high-frequency instability is a practical marker of system strength (Qu & Hao, 2022). Therefore, the outcome structure in the findings reinforced earlier arguments for multi-domain biosecurity measurement, confirming that microbial, process, event, and stability outcomes together provide the most faithful portrait of chain biosecurity performance.

Finally, the discussion considered how these findings collectively refined the understanding of biosecurity in global food distribution chains. Earlier literature provided strong evidence that HACCP reduces hazards and that ISO stabilizes management behavior, yet much of that evidence was plant bounded or certification categorical. This study demonstrated that maturity depth and integration intensity were more informative than simple adoption status, and that their predictive influence extended across routes, partners, and border interfaces (Yang & Yang, 2023). The findings therefore deepened earlier system-based interpretations by showing that chain biosecurity depends on both technical precision and governance consistency enacted together. The evidence also underscored that distribution corridors are not peripheral to food safety; they are biosecurity arenas where preventive maturity is tested continuously through thermal control, hygienic handling, and partner alignment. By confirming synergy and contextual moderation, the results supported the long-standing preventive principle that hazards are controlled most reliably when barriers are layered, verified, and harmonized across every handoff (Cheng et al., 2021). The pattern of mediation and moderation further harmonized with earlier theoretical accounts that positioned monitoring discipline, prerequisite verification, cold-chain sensitivity, and regulatory interfaces as decisive pathways for hazard amplification or containment. Overall, the discussion indicated that chain-level biosecurity enhancement was best explained by a structured triad: mature HACCP technical control, mature ISO governance, and deep integration that aligns both across nodes. This triad clarified why some global distribution chains reached high microbial compliance with low volatility, while others experienced recurrent deviations and visible disruptions despite nominal preventive adoption (Li & Ding, 2022).

CONCLUSION

HACCP and ISO frameworks were positioned in global food distribution scholarship as complementary pillars for enhancing biosecurity because they addressed biological hazards through different but interlocking logics that operated across complex, multi-node supply networks. HACCP functioned as the technical core of prevention, requiring systematic hazard analysis, identification of critical control points, setting biologically defensible limits, continuous monitoring, corrective containment, and verification, thereby transforming microbiological risk knowledge into measurable barriers that travelled with food through processing, storage, transportation, cross-docking, and retail holding. ISO food safety management standards, especially ISO 22000, functioned as chain-level governance architecture that embedded HACCP into an auditable management system, formalizing prerequisite programs such as sanitation, pest control, transport hygiene, equipment maintenance, and personnel competency, and obligating leadership commitment, document control, traceability readiness, internal and external communication routines, periodic audits, and corrective-preventive action closure. In global distribution corridors where products crossed multiple borders, climates, and handling environments, biological hazards were repeatedly amplified by time–temperature abuse, cross-contamination at transfer interfaces, supplier variability, and uneven enforcement regimes; therefore, biosecurity depended not only on correct technical controls at isolated nodes, but on consistency and accountability across all chain partners. HACCP maturity, reflected in the breadth and risk-ranking accuracy of hazard analysis, the alignment of CCPs with high-risk logistic steps, the clarity and validity of critical limits, the rigor and completeness of monitoring records, the speed and precision of corrective actions, and the independence of verification, was associated with lower pathogen prevalence, fewer deviation events, improved cold-chain stability, and stronger destination compliance because hazards were intercepted before they could expand during distribution. ISO maturity, reflected in audit conformance strength, verified prerequisite reliability, broad training coverage, and rapid corrective closure, was associated with reduced recurrence of hygiene failures, lower compliance variance between facilities and suppliers, tighter traceability performance, and fewer disruptive events such as recalls or border rejections because governance standardized behavior and evidence across organizations. The integrated application of HACCP within ISO systems generated a synergistic biosecurity advantage: ISO audit cycles strengthened HACCP monitoring discipline, prerequisite standardization reduced background biological load and thereby decreased CCP breaches, and formalized supplier and logistics communication reduced upstream hazard entry and accelerated downstream containment. Consequently, integration depth emerged as a chain capability that exceeded the influence of either framework alone, especially in cold-chain dominant and border-dense routes and in high-risk commodities where small control lapses rapidly translated into biological failure. Overall, the combined HACCP–ISO architecture enhanced global food biosecurity by linking precise technical hazard control to stable, harmonized managerial governance, enabling distribution chains to maintain low-volatility biological safety performance despite distance, complexity, and heterogeneous regulatory environments.

RECOMMENDATION

Recommendations for strengthening biosecurity in global food distribution chains through HACCP and ISO frameworks should prioritize depth, integration, and chain-wide consistency over symbolic adoption. First, organizations should treat HACCP maturity as a measurable capability and continuously refine hazard analyses to include post-processing and distribution realities, ensuring that biological risks linked to storage atmospheres, pallet and container reuse, cross-docking interfaces, mixed-load transport, border dwell times, and retail holding conditions are explicitly mapped and risk-ranked. Critical control points should be revalidated across the full corridor, not only within processing plants, so that cold-chain transfer windows, loading sanitation transitions, vehicle temperature maintenance, and segregation points are controlled with biologically justified limits and monitoring frequencies matched to risk intensity. Second, ISO 22000 governance should be embedded as a daily operating discipline across every distribution node, with senior leadership visibly accountable for resource allocation, enforcement of food safety policy, and routine management review of trend evidence from CCP deviations, temperature excursions, and supplier nonconformities. Prerequisite programs and operational prerequisites require equal emphasis in warehouses, vehicles, port facilities, and transshipment hubs, since background hygiene failures are dominant biosecurity entry routes outside CCPs; sanitation verification, pest/vector control, equipment maintenance, zoning, transport cleanliness, and water/air quality safeguards should therefore be audited on a recurring cycle and closed through corrective-preventive action systems with documented root-cause elimination. Third, suppliers and logistics partners should be incorporated into a unified HACCP-within-ISO control architecture using shared documentation standards, aligned audit criteria, and explicit incident-communication requirements so that deviations detected upstream are escalated quickly and contained before hazards propagate. This includes contractual alignment on CCP/OPRP expectations, mutual access to traceability records, and harmonized training requirements for third-party handlers. Fourth, monitoring systems should shift toward real-time reliability by expanding calibrated telemetry for temperature and hygiene-sensitive controls, enforcing record completeness through digital capture where feasible, and using verification sampling and deviation trend analysis to recalibrate limits and revise hazard priorities. Fifth, firms operating in border-dense routes should use ISO reporting language and traceability formats that are interoperable with importing-market inspection requirements, reducing compliance fragmentation and shortening the time hazards remain uncontrolled during regulatory transitions. Sixth, performance evaluation should adopt multi-domain biosecurity dashboards that combine microbial compliance at destination with process stability indicators such as CCP deviation frequency, temperature excursion behavior, recall or rejection incidence, and supplier-dispersion patterns, because chain risk is defined by weak links and volatility rather than by averages alone. Finally, sector regulators, certification bodies, and major buyers should encourage maturity-based assessment by rewarding demonstrable integration depth and corridor-level performance stability, thereby shifting incentives from certificate possession to verifiable biosecurity capability across the entire global distribution network.

LIMITATIONS

Several limitations characterized the quantitative examination of HACCP and ISO frameworks for enhancing biosecurity in global food distribution chains and should be considered when interpreting the findings. First, the study relied on observational data drawn from operating firms rather than controlled experimental assignment, so causal interpretation remained bounded by the possibility that unmeasured organizational characteristics co-varied with maturity levels. Although extensive controls captured commodity risk class, chain length, cold-chain dependency, shipment volume, border-transition density, firm size, and enforcement strictness, additional contextual factors such as informal safety culture, buyer surveillance pressure, regional infrastructure reliability, or workforce turnover may have influenced both preventive maturity and biosecurity outcomes. Second, maturity indices were derived from audit evidence and operational records, which were subject to the completeness and accuracy of documentation practices within each chain. Even with strong inter-rater agreement and coherent validity structure, audit-based scoring could not fully eliminate the risk of reporting bias where records overstated monitoring rigor or corrective closure performance. Third, distribution-corridor outcomes depended on heterogeneous data sources across countries and partners, and this heterogeneity may have introduced measurement noise. Microbial compliance data, for example, were aggregated from destination testing regimes that varied in sampling intensity, laboratory capacity, and regulatory thresholds across markets, which may have affected comparability of pass rates across routes. Similarly, temperature excursion indicators were generated from telemetry systems that differed by device type, calibration schedules, recording intervals, and data-retention policies, creating uneven granularity across chains. Fourth, event outcomes such as recalls and border rejections were relatively infrequent within the observation window and were influenced by external surveillance intensity and disclosure rules, so statistical sensitivity for those outcomes was lower than for high-frequency process indicators such as CCP deviations or temperature excursions. Fifth, integration depth measurement, while conceptually comprehensive, remained constrained by available documentation of partner alignment and shared governance routines; soft coordination practices or informal knowledge transfers between suppliers and logistics actors were difficult to quantify and may have contributed to synergy beyond recorded integration indicators. Sixth, the multi-level structure of the dataset captured shipments nested within routes and firms, yet some chains provided fewer observable shipments or shorter route histories than others, which may have reduced precision for route-level stability estimates in smaller sub-samples. Seventh, while the sample spanned multiple trade corridors and commodity classes, participation depended on firm willingness and record accessibility, so selection effects may have occurred if higher-performing or more compliance-oriented organizations were more likely to share complete datasets. Finally, the analytic focus centered on biological hazards and related preventive controls, and it did not directly incorporate chemical or physical hazard pathways that can interact with biosecurity through shared prerequisite systems, meaning the conclusions were specific to biological risk performance rather than to food safety in its widest multi-hazard sense. Taken together, these limitations indicated that the reported relationships were robust within available corridor data and measurement logic, yet they remained conditioned by observational scope, record fidelity, cross-country data heterogeneity, and the inherent difficulty of fully quantifying chain-wide integration in complex global distribution networks.

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