



Review Article

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Safeguarding School Meals at Scale: Contamination Risk Amplification and End-to-End Mitigation Across Large-Scale School Food Provision Systems - A Review

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Abstract

Large-scale school meal programmers can improve nutrition, educational participation, food access, and social protection, but their scale also creates distinctive food-safety challenges. A localized failure in sourcing, preparation, cooking, holding, transportation, or serving can potentially expose large numbers of students simultaneously. This qualitative literature review examines contamination pathways and mitigation strategies across the entire school-meal chain, from supplier qualification and raw-material procurement to kitchen processing, transportation, school-level receiving, serving, surveillance, and outbreak response. The synthesis identifies biological hazards as the most immediate drivers of acute foodborne illness while recognizing additional risks from allergens, chemical contaminants, mycotoxins, food-contact materials, and emerging contaminants. Large-batch production, environmental persistence, post-cooking handling, time-temperature deviations, cross-contamination, extended transport, and multi-school distribution are identified as major amplification mechanisms. Effective risk management consequently requires a defence-in-depth approach integrating supplier assurance, hygienic design, GMP/GHP, HACCP-based controls, environmental monitoring, validated cooking and holding procedures, controlled transportation, school-level receiving verification, food-safety culture, rapid diagnostics, traceability, and early-warning systems. The review proposes an end-to-end risk-amplification framework and a twelve-layer mitigation architecture for large-scale school-meal systems. The framework emphasizes that food safety is a continuous system property rather than the responsibility of a single kitchen or critical control point.

Keywords: School meals, School feeding, Food contamination, Foodborne illness, Centralized catering, Food safety management, HACCP, Time-temperature control, Food safety culture, Food traceability

JEL Classification: I18, I21, L66, Q18, D81

Introduction

School meal programmes operate at the intersection of nutrition, education, public health, agriculture, logistics, and social protection. When designed and implemented effectively, they can improve children's access to nutritious food while reducing the burden of meal provision on households. Expansion from relatively

small school-based foodservice operations toward large-scale centralized kitchens or contracted catering systems can additionally generate economies of scale, standardized procurement, professional food preparation, and greater operational consistency. However, the same characteristics that enable efficient mass

feeding can also magnify the consequences of food-safety failures because one contaminated ingredient, one inadequately controlled batch, or one persistent environmental source may be connected to thousands of meals distributed to multiple schools [27,28]. Recent literature explicitly identifies this duality. *Li, et al., (2026) [27]* describe centralized school catering as capable of improving efficiency and standardized management while simultaneously concentrating microbial risks because a single contamination event may affect large numbers of students. They particularly emphasize time-temperature monitoring and predictive approaches as emerging opportunities for strengthening safety in centralized systems. The food-safety problem in school feeding must consequently be distinguished from the broader nutritional quality of school meals. A nutritionally balanced meal can still be unsafe when biological contamination, allergen cross-contact, hazardous chemical exposure, or inappropriate temperature conditions are present. Conversely, food that is microbiologically safe may still perform poorly nutritionally. Although these dimensions interact within school-food governance, this article focuses specifically on contamination and foodborne health risks throughout the food-provision chain.

Children also constitute an important population for food-safety protection. School meal programmes concentrate consumers of similar age within common consumption windows, consequently, contaminated meals may generate recognizable clusters of illness over short intervals. The problem becomes particularly consequential when a central production facility supplies multiple schools because cases may occur simultaneously across geographically separated locations. Historical and recent school-associated outbreaks demonstrate that a common source can rapidly become a multi-school public-health event [5,17,23]. For example, *Kashima, et al., (2021) [23]* investigated a large Japanese food-poisoning event associated with school lunches and an atypical *Escherichia coli* strain, illustrating how common-source contamination within a school-meal system can produce extensive population exposure. *Hirose, et al., (2023) [17]* similarly examined a milk-associated outbreak spanning numerous schools. These examples are important not because centralized provision is inherently unsafe, but because they show the potential magnitude of consequences when common-source food reaches many schools before the hazard is detected. Recent empirical evidence also identifies the importance of post-cooking handling. *Xie, et al., (2020) [61]* assessed ready-to-eat foods in school cafeterias in Chongqing and found that foods subjected to thermal processes and maintained hot generally showed better microbiological quality than fresh foods or cooked foods undergoing subsequent cutting, cooling, ingredient addition, or other post-cooking manipulation. Their results highlight a central principal of school-food safety: a validated cooking step does not guarantee final-product safety if subsequent handling provides opportunities for recontamination.

The problem is similarly visible in lower-resource settings. *Tamiru, et al., (2024) [51]*, examining ready-to-eat foods in the Addis

Ababa School Feeding Program, reported generally acceptable food results but also identified microbiological concerns in drinking-water samples and variation among prepared foods. Approximately 23.4% of sampled drinking-water specimens were categorized as non-potable in that study, illustrating why water must be treated as an integral component of the school-meal safety system rather than merely as an external utility. Time-temperature failures constitute another recurring pathway. *Biggel, et al., (2026) [5]* investigated a school-canteen outbreak involving 27 children following consumption of a hot ready-to-eat macaroni dish. The investigation implicated emetic *Bacillus cereus* and identified inadequate temperature control during food holding, demonstrating how the interval after cooking can determine whether surviving organisms or spores develop into an acute intoxication hazard. The Indonesian context reinforces the importance of constructing food-safety architecture alongside large-scale school-feeding expansion. *Rachmadewi, et al., (2021) [42]*, based on research in selected Indonesian schools, highlighted the need for comprehensive guidelines, stakeholder capacity strengthening, improved implementation, and stronger monitoring of school canteens. More recently, *Surendra, et al., (2026) [50]* argued that food-safety surveillance, outbreak detection, and response capacity require particular attention in Indonesia's expanded school-meal programme. Their published analysis reported numerous suspected food-poisoning events during programme expansion, because not all reported events had laboratory-confirmed etiologies, those figures should be interpreted as authors' reported programme surveillance findings rather than as a complete microbiologically confirmed outbreak count [50].

The central proposition of this article is therefore that scale primarily amplifies consequences rather than automatically creating hazards. The biological organism present in a central kitchen may be identical to one found in a small cafeteria, but its potential effect differs when production involves very large batches, shared equipment, extended holding, simultaneous dispatch, multiple vehicles, and delivery to many schools. Production scale changes the topology of exposure. This distinction permits school-meal safety to be conceptualized as an amplification pathway. A hazard is first introduced through ingredients, water, personnel, equipment, or the environment. It may subsequently survive or persist, move through cross-contamination, multiply under permissive time-temperature conditions, become incorporated into a large batch, travel across logistics networks, and finally reach students. The ultimate number of illnesses therefore depends not only on whether contamination occurs but also on how many opportunities exist to stop its propagation. The article addresses eight research questions concerning major hazards, contamination entry points, risk amplification through centralization, the roles of time-temperature management and cross-contamination, the effectiveness of conventional food-safety systems, human and organizational reliability, emerging monitoring technologies, and an integrated end-to-end governance model. These questions

are addressed through a thematic synthesis that links hazard introduction, amplification, surveillance, containment, and organizational learning across the complete school-meal chain. Accordingly, this qualitative literature review aims to integrate evidence from school foodservice, institutional catering, food microbiology, environmental monitoring, supply-chain management, rapid pathogen detection, allergen management, traceability, and organizational food-safety culture. The intended contribution is a coherent model showing how school-meal risks should be controlled continuously—from supplier to student—rather than through isolated inspection of the final meal.

Literature Review

Conceptualizing Contamination Risk in School Meals

Food-safety risk depends on both the presence of hazards and the probability and magnitude of exposure. Biological, chemical, allergenic, and physical hazards therefore require different control strategies. Biological organisms can survive, multiply, form spores, establish persistent environmental niches, or produce toxins, chemical contaminants generally do not multiply but may persist or accumulate, allergens can trigger reactions at relatively low exposures in susceptible children, and physical hazards depend on material introduction and detection. This heterogeneity makes a universal notion of “zero contamination” operationally inadequate. Instead, school-meal systems require hazard-specific prevention, critical limits, acceptance criteria, monitoring, verification, and corrective action. For biological hazards, these may include thermal lethality, refrigeration, sanitation, and environmental monitoring. For allergens, the central mechanisms are ingredient control, segregation, cleaning validation, formulation management, and labelling. Chemical hazards require supplier assurance, specification control, analytical surveillance, and appropriate food-contact materials [12,43,53]. The epidemiological distinction between foodborne infection and intoxication is also important. *Salmonella*, pathogenic *E. coli*, *Campylobacter*, and *Listeria monocytogenes* primarily create infection hazards, whereas *B. cereus* or *Staphylococcus aureus* may cause illness through preformed toxins under particular conditions. Consequently, heating food immediately before serving may reduce viable cells but may not necessarily neutralize toxins already formed in food. This difference makes prevention of inappropriate holding particularly important for cooked rice, pasta, sauces, and other foods potentially supporting toxin production [11,22,54].

Biological Hazards in School-Food Systems

School-meal systems can encounter microbial hazards at virtually every stage. Raw poultry can carry *Campylobacter* or *Salmonella*, produce can acquire pathogens from irrigation water, soil, manure, washing, or handling, spices and dry ingredients can introduce resistant organisms, employees can transfer organisms through inadequate hand hygiene, and environmental reservoirs can contaminate cooked foods after thermal processing [37,48].

Bacillus cereus deserves particular attention in institutional feeding because of its environmental ubiquity, spore formation, ability to survive some thermal processes, and capacity to produce diarrhoeal or emetic toxins. The risk becomes pronounced when cooked foods are held within temperature ranges that permit germination and growth. Contemporary reviews therefore emphasize that control requires attention not merely to cooking but to the complete cooling, holding, storage, reheating, and serving profile [7,8,22]. The 2026 school-canteen investigation provides contemporary empirical support for this principle [5].

Listeria monocytogenes presents a different risk architecture. Its relevance arises from environmental persistence, tolerance of refrigeration, and capacity to form or participate in biofilms. Although invasive listeriosis is less commonly discussed in relation to routine school outbreaks than gastroenteritis-producing organisms, *Listeria* illustrates why ready-to-eat foods and post-lethality environments require stringent environmental control [18,32,60].

Antimicrobial resistance adds a wider One Health dimension. Resistant organisms and resistance determinants may circulate among agriculture, animals, environmental reservoirs, processing environments, foods, and humans. Although resistance is not itself equivalent to contamination, food-chain transmission can complicate clinical management and surveillance, strengthening the case for integrated microbiological monitoring [44].

Environmental Persistence, Biofilms, and Cross-Contamination

Cross-contamination is one of the most important mechanisms by which an initially localized hazard becomes distributed across school meals. Raw and cooked products may share work surfaces, knives, cutting boards, containers, trolleys, sinks, gloves, employee pathways, or storage areas. In central kitchens, the number of contact events and meals handled per shift can multiply the impact of inadequate zoning. Biofilms further complicate sanitation. Food-industry biofilms consist of microbial communities associated with surfaces and extracellular matrices that can increase persistence and tolerance to cleaning or sanitizing conditions. Drains, joints, conveyor components, fillers, gaskets, slicers, and other inaccessible sites can become environmental reservoirs that intermittently release organisms into food or food-contact environments [4,6,13]. This creates a conceptual distinction between episodic contamination and persistent contamination. An unsafe ingredient may affect one delivery or production lot, whereas an established environmental reservoir can affect multiple batches over multiple days. In a centralized school-meal kitchen, persistent contamination therefore has the potential to link temporally separate deliveries to the same environmental source. Environmental Monitoring Programs (EMPs) are designed partly to identify these hidden risks. Mota, et al., (2021) [33] characterize environmental monitoring as an important complement to product testing and emphasize that no one-size-fits-all design exists, site selection, indicators, sampling

frequency, trend interpretation, and corrective actions should instead reflect facility-specific risk.

Chemical Hazards, Allergens, and Emerging Contaminants

Microbial food poisoning is generally the most immediate concern in large-scale school feeding, but it is not the only safety issue. Mycotoxins can enter through cereals, nuts, spices, and other commodities. Their management depends primarily on upstream agricultural, storage, supplier, and analytical controls because cooking does not reliably eliminate all mycotoxin hazards [20,24,26].

Heavy metals and persistent environmental pollutants may enter the food chain through contaminated water, soils, ingredients, or environmental pathways. PFAS have similarly attracted food-safety attention because of environmental persistence and analytical complexity [35,46,52]. Endocrine-disrupting chemical contaminants and micro- or nanoplastics represent additional long-term exposure questions, although risk characterization for some emerging contaminants remains considerably less mature than for established microbial hazards [40,47,56].

Process contaminants also require balance between microbiological safety and chemical quality. Acrylamide formation in heat-treated carbohydrate-rich foods illustrates that greater heat exposure does not always translate into unambiguously better overall safety. Process validation should therefore consider microbiological lethality alongside product-specific chemical changes [45]. Food-contact materials represent another pathway. Packaging used for hot meals may encounter elevated temperatures and prolonged contact periods before consumption. Migration therefore depends on material composition, temperature, contact duration, and food characteristics. Selection of compliant food-contact materials should be integrated into procurement specifications rather than treated as an afterthought [53,57]. Allergens deserve particularly careful treatment in school environments because susceptible children may experience severe reactions even when most students remain unaffected. Cross-contact can occur through shared equipment, utensils, ingredients, airborne powders, rework, serving implements, or incorrect packaging. Effective allergen management therefore requires ingredient mapping, segregation, validated cleaning, communication, and accurate meal identification rather than merely precautionary labels [12,21,30,43,]. Evidence on allergen cross-contact management emphasizes the importance of mapping transmission vectors and corresponding controls.

Method

This study adopts a **qualitative literature review** rather than a systematic literature review. The objective is interpretive integration of evidence across fields rather than exhaustive identification of every publication meeting predetermined criteria. Accordingly, the review does not claim PRISMA-based comprehensiveness, pooled statistical estimation, or formal meta-analytic inference. The literature base prioritizes peer-reviewed research published between 2020 and 2026 in food microbiology, school foodservice,

institutional catering, environmental monitoring, food engineering, public health, allergen management, food-safety culture, diagnostics, and supply-chain traceability. Relevant journals include Food Control, Food Research International, Journal of Food Protection, Current Opinion in Food Science, Comprehensive Reviews in Food Science and Food Safety, Trends in Food Science & Technology, International Journal of Food Microbiology, Foods, Frontiers in Microbiology, British Food Journal, Food and Nutrition Bulletin, and related journals. Literature identification was conceptually driven around combinations of terms such as school meals, school feeding, central kitchen, school cafeteria, centralized catering, foodborne outbreak, food poisoning, cross-contamination, time-temperature control, *Bacillus cereus*, *Salmonella*, *Listeria*, food safety culture, HACCP, environmental monitoring, rapid pathogen detection, food traceability, IoT, and early warning system. Search terms were iteratively refined as new conceptual links emerged, consistent with the interpretive rather than exhaustive purpose of a qualitative literature review.

The analytical approach consisted of iterative thematic coding. First-order codes represented concrete hazards and processes, including raw materials, water, cross-contamination, cooking, cooling, holding, transport, serving, personnel, biofilms, supplier verification, and outbreak detection. Second-order coding grouped these into broader mechanisms of hazard introduction, persistence, transfer, amplification, detection, containment, and learning. A third analytical step mapped these mechanisms onto the physical school-meal chain. This produced an end-to-end architecture extending from procurement and supplier assurance through centralized production and transport to school-level receipt and consumption. The final interpretive synthesis identifies where risk can increase, where it can be interrupted, and where preventive and reactive controls must overlap. Because the article is qualitative rather than systematic, numerical findings from individual studies are used to illustrate specific mechanisms rather than estimate universal prevalence. Contemporary school-outbreak investigations are interpreted alongside broader food-industry literature because some critical mechanisms—including biofilms, rapid diagnostics, environmental monitoring, allergen cross-contact, and high-pressure processing—are supported more strongly by the wider food-safety literature than by school-specific studies alone.

Results: Thematic Findings

Theme 1: Centralization Produces both Standardization and Risk Concentration

Centralized meal production can create strong food-safety advantages. Standard operating procedures, specialized personnel, dedicated quality-control teams, standardized recipes, automated monitoring, controlled procurement, and consolidated training can all be easier to implement in a professionally operated central kitchen than across numerous small decentralized sites. Nevertheless, formalized procedures should be complemented by independent verification: a 2024 investigation of 10 school kitchens found that external auditors identified weaknesses in personal hygiene, storage, cleaning, and disinfection more critically

than internal self-checks, indicating that self-assessment alone can overestimate operational conformity [55]. Nevertheless, centralization simultaneously creates common-mode failure potential. If many schools depend upon the same ingredients, kitchen, preparation line, transport system, or supplier, a single failure can cross institutional boundaries. *Li, et al.*, (2026) [28] identify exactly this structural issue: central catering can improve efficiency while concentrating microbial risk because contamination may affect thousands of students simultaneously.

Scale therefore has two opposing effects. It may reduce the probability of some failures through professionalization and standardization, but it can increase the consequence of failures that escape control. This distinction is essential because it avoids the

simplistic conclusion that centralized systems are inherently safer or inherently more dangerous.

Figure 1 conceptualizes the complete school-meal chain and demonstrates that the safety boundary does not end at the central kitchen. Every handover between organizations or process stages creates a potential hazard-control interface.

Figure 1 emphasizes that the food-safety outcome observed at consumption is produced by the cumulative performance of the whole chain. A properly cooked meal can become unsafe during cooling, transport, temporary school storage, portioning, or serving. Conversely, risks entering through raw materials can be eliminated when subsequent validated controls function correctly.

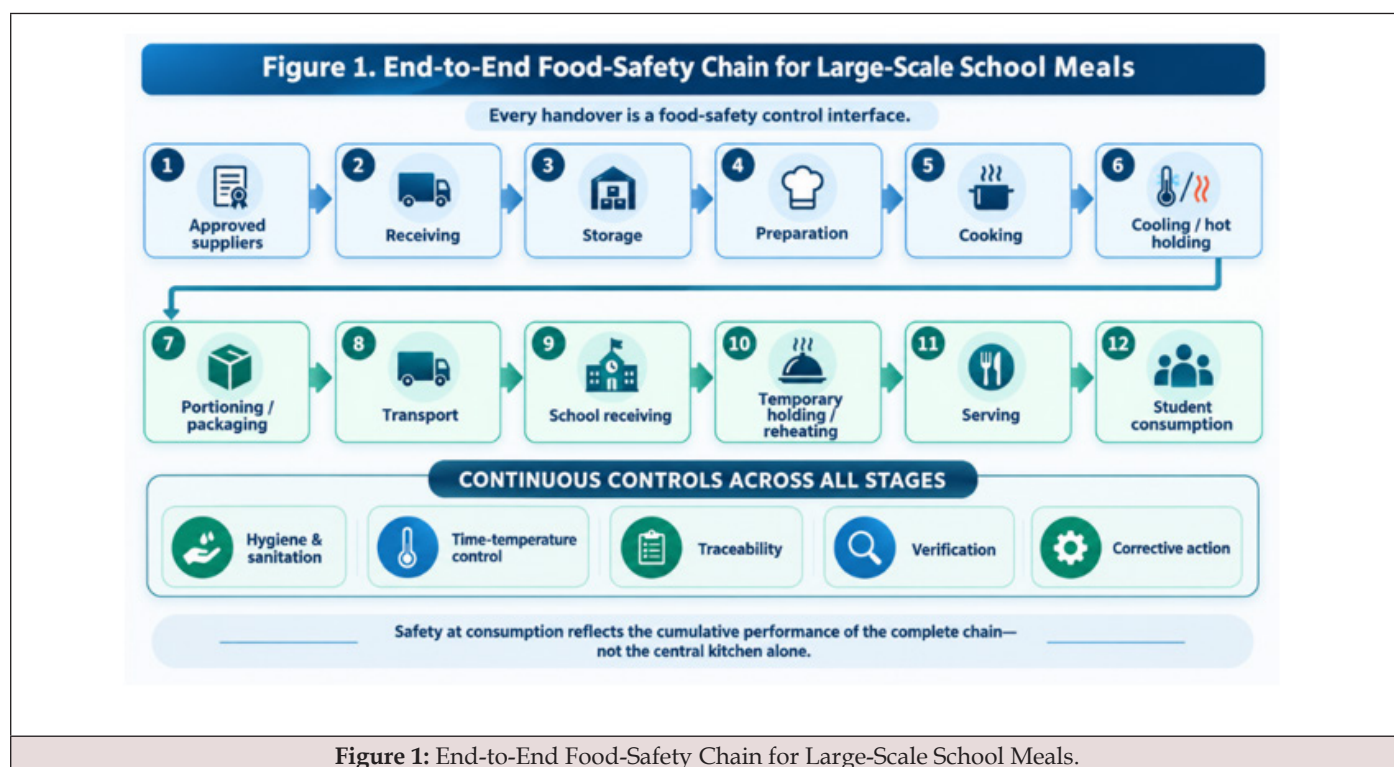


Figure 1: End-to-End Food-Safety Chain for Large-Scale School Meals.

Theme 2: Upstream Contamination Determines the Starting Hazard Load

Supplier assurance represents the first barrier. Ingredients may arrive carrying pathogenic microorganisms, spores, mycotoxins, pesticide residues, chemical contaminants, allergens, or foreign materials, and the initial hazard load can be especially consequential when foods receive little subsequent lethality treatment. Evidence from school-feeding schemes has shown substantial microbiological contamination and antimicrobial resistance in fresh produce, reinforcing the need to integrate primary-production and supplier controls into school-meal safety governance [34]. Supplier controls should include specifications, approved-source requirements, risk-based audits, certificates where appropriate, cold-chain verification, allergen declarations, traceability, microbiological criteria, rejection procedures, and mechanisms for supplier corrective action. Centralized procurement can facilitate these controls because

specifications can be standardized, although excessive dependence on a single supplier can also increase system-wide exposure if a contaminated ingredient enters production.

The role of raw-material contamination becomes particularly important when ingredients undergo little or no subsequent lethality treatment. Fresh fruit, raw vegetables, garnishes, and post-cooking additions require stricter upstream and handling controls than ingredients entering a validated cooking process. The Chongqing school-cafeteria study found poorer microbiological indicators in foods exposed to nonthermal or post-cooking handling than in foods subjected to cooking and hot holding [61], while South African school-feeding research identified microbiological and antimicrobial-resistance concerns in fresh produce supplied to schools [34]. Water should be managed as an ingredient, processing aid, sanitation input, and hygiene requirement. The findings from Addis Ababa demonstrate that water quality can remain an important weakness even where cooked meals perform reasonably well microbiologically [51].

Theme 3: Kitchen Operations can Transform Contamination into Amplified Exposure

The central kitchen is the primary transformation point where ingredients converge into high-volume batches. This convergence enables efficient production but also permits contamination to spread from one ingredient, surface, worker, or piece of equipment into hundreds or thousands of meal portions. Raw-to-cooked separation is consequently fundamental. Hygienic zoning should control the movement of employees, tools, containers, trolleys, and waste between raw and ready-to-eat areas. Equipment should be designed for effective cleaning and should not contain inaccessible niches capable of harbouring microorganisms. Cooking represents one of the strongest microbial barriers, but its effectiveness depends on validated time-temperature combinations, appropriate measurement locations, calibrated thermometers, loading patterns, food thickness, and equipment performance. "Cooking completed" is therefore not an adequate control record unless a validated critical limit has actually been achieved. Post-cooking handling then becomes critical. Cutting, portioning, sauce addition, packaging, and manual assembly can reintroduce pathogens after the main lethality step. Xie, *et al.*, (2020) [61] demonstrated that this category of food showed greater microbiological concerns in school cafeterias, reinforcing the need to treat post-lethality zones as high-care environments. Environmental persistence can make the problem recurrent rather than episodic. Biofilm research indicates that established microbial communities on food-contact

or adjacent surfaces can resist ordinary sanitation and repeatedly contaminate food production environments [4,6,13,18,32,37]. Environmental monitoring therefore provides a mechanism for finding the conditions enabling contamination rather than waiting until contaminated meals are identified.

Theme 4: Time-Temperature-Logistics is the Critical Interface between Kitchen and School

Large-scale school catering introduces a period not always present in onsite cooking: substantial elapsed time between meal completion and consumption. During this interval, meals may be portioned, packaged, loaded, transported through variable environmental conditions, unloaded, temporarily held, reheated, distributed, and consumed. Microbial behaviour continues throughout this period. A cooked food is not biologically static. Surviving organisms can grow if conditions permit, while spores may germinate. The *B. cereus* literature demonstrates why cooked starch-rich foods require effective temperature management [8,11,22]. The 2026 school outbreak associated with inadequate holding temperature provides a direct contemporary example [5]. Transport should therefore be considered an active food-safety process, not merely a logistical movement. Requirements include suitable insulated containers or vehicles, defined maximum transport times, temperature verification before dispatch and at receipt, calibrated monitoring devices, cleaning and sanitation of food transport equipment, route contingency planning, and documented action limits.

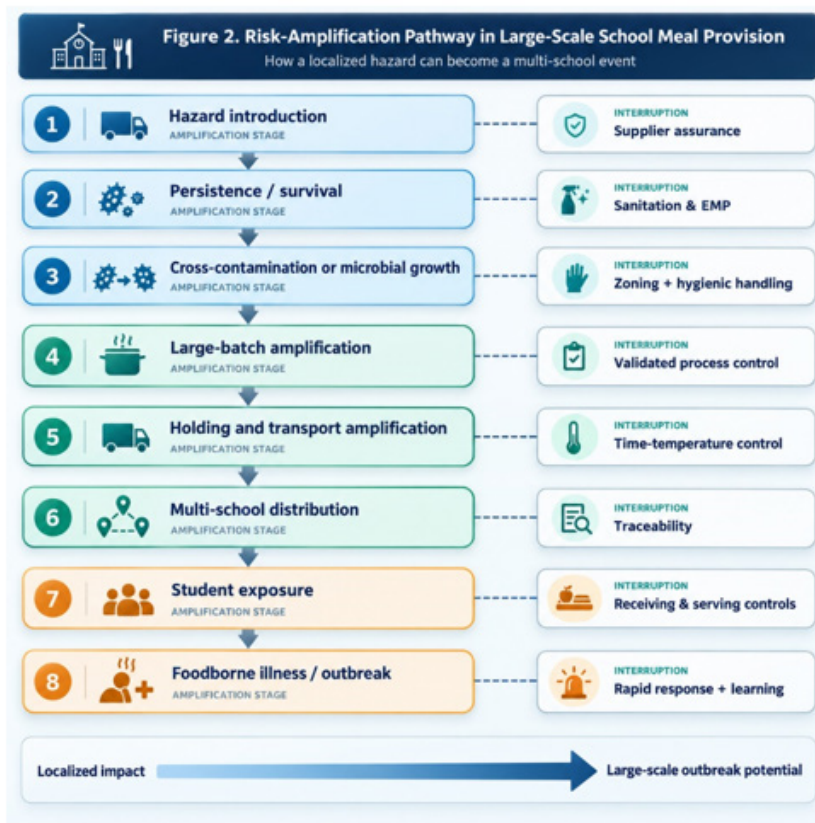


Figure 2: Risk-Amplification Pathway in Large-Scale School Meal Provision.

Figure 2 illustrates how an initiating hazard can accumulate amplification factors between procurement and student exposure. It distinguishes hazard presence from the mechanisms that convert one failure into a large-scale event (Figure 2).

The conceptual value of Figure 2 lies in showing multiple opportunities for interruption. Supplier control can prevent hazard introduction, sanitation can limit persistence, zoning can prevent transfer, validated cooking can reduce microbial loads, temperature control can prevent growth, receiving verification can reject unsafe deliveries, and traceability can contain products after an incident has been detected.

Theme 5: The Receiving School is an Active Control Point

A frequent conceptual error is to treat the school's role as beginning only when food is served. In centrally prepared systems, however, the school is effectively the final receiving node of a food supply chain and must therefore perform food-safety functions comparable to those of a commercial receiving operation. Receiving personnel should verify delivery identity, lot or dispatch information, packaging integrity, temperature, arrival time, and unusual sensory or physical conditions. Deviations should trigger predefined decisions rather than ad hoc negotiation with drivers or kitchen staff. A meal outside a defined acceptance temperature should not automatically continue to students simply because large numbers are waiting to eat. The operational system must therefore include contingency meals, escalation authority, rejection criteria, and communication channels that allow food-safety decisions without disproportionate pressure to prioritize service continuity. Temporary storage is equally important. Meals arriving earlier than anticipated may experience extended holding before serving. If schools lack suitable hot-holding or refrigeration equipment, logistical planning must compensate through shorter delivery-to-consumption intervals. Serving introduces additional hand-contact and environmental exposure. Appropriate utensils, hand hygiene, controlled distribution areas, allergen identification, and avoidance of uncontrolled rehandling are therefore required. This last-mile perspective extends the food-safety responsibility from the producing organization to the entire delivery network.

Theme 6: Human Reliability and Food-Safety Culture Determine Whether Procedures Work

Food-safety systems operate through human decisions. Training improves knowledge and can improve practice, but evidence indicates that knowledge gains alone do not guarantee consistent behaviour. A meta-analysis by *Insfran-Rivarola, et al., (2020)* [19] found positive effects of food-safety training on knowledge, attitudes, and practices, while also showing that improvements in observed behaviour are generally smaller than improvements in knowledge. This gap supports combining training with supervision, verification, feedback, and organizational reinforcement rather than treating classroom instruction as a sufficient intervention. This gap between knowing and doing makes food-safety culture especially important. *Fujisaki and Akamatsu (2020)* [15] developed

a school-foodservice-specific culture assessment covering risk underestimation, surrounding support, communication, facilities and equipment, and commitment. Their large sample of Japanese school food handlers demonstrates that school foodservice culture can be operationalized and measured rather than treated as an abstract concept, while later work has emphasized that diagnosis and gap analysis should be connected to deliberate improvement interventions [49].

Food-safety culture becomes particularly consequential in mass production because high throughput creates production pressure. Workers may experience incentives to avoid slowing a line, discarding large batches, reporting temperature failures, or delaying dispatch. Management must therefore ensure that food-safety escalation is organizationally rewarded rather than punished. Research in broader foodservice contexts reinforces this conclusion. *Zanin, et al., (2021)*, *Colom Umbert, et al., (2023)*, *Spagnoli, et al., (2023)*, *Pai, et al., (2024)*, and *Liggins and Kim (2024)* [9,29,36,49,65,] emphasize leadership, communication, organizational support, behavioural enactment, and verification as components of food-safety culture. Training should consequently be integrated with supervision, adequate staffing, facility design, feedback, management accountability, and mechanisms that compare self-reported compliance with observable practice.

Theme 7: Surveillance must become Continuous Rather than Episodic

Finished-product testing cannot guarantee that every meal is safe because only a small fraction of total output can be sampled. Surveillance should therefore combine multiple information streams: supplier verification, environmental sampling, process-temperature records, food testing, transport logs, receiving records, student illness signals, complaints, and epidemiological surveillance. Rapid diagnostics can shorten the interval between sampling and decision-making. Portable biosensors, nucleic-acid detection, point-of-care systems, and microfluidics may eventually support more decentralized food-safety testing, although sample preparation, enrichment requirements, matrix interference, validation, and cost remain important constraints [10,16,31,38,41,66]. Biosensor research targeting *Listeria*, *Salmonella*, *Campylobacter*, and *E. coli* illustrates the potential for faster food-testing workflows. Predictive microbiology provides another layer by estimating microbial behaviour under changing conditions. Incorporating food matrix and microstructure improves realism but also increases model complexity (*Verheyen and Van Impe, 2021*) [59]. For centralized catering, predictive models could potentially be linked with continuous temperature histories to identify meals experiencing higher growth potential during transport or holding.

Figure 3 presents the proposed time-temperature surveillance system across the interval between cooking and consumption. Rather than relying on one temperature measurement, the model treats thermal integrity as a continuous history (Figure 3).

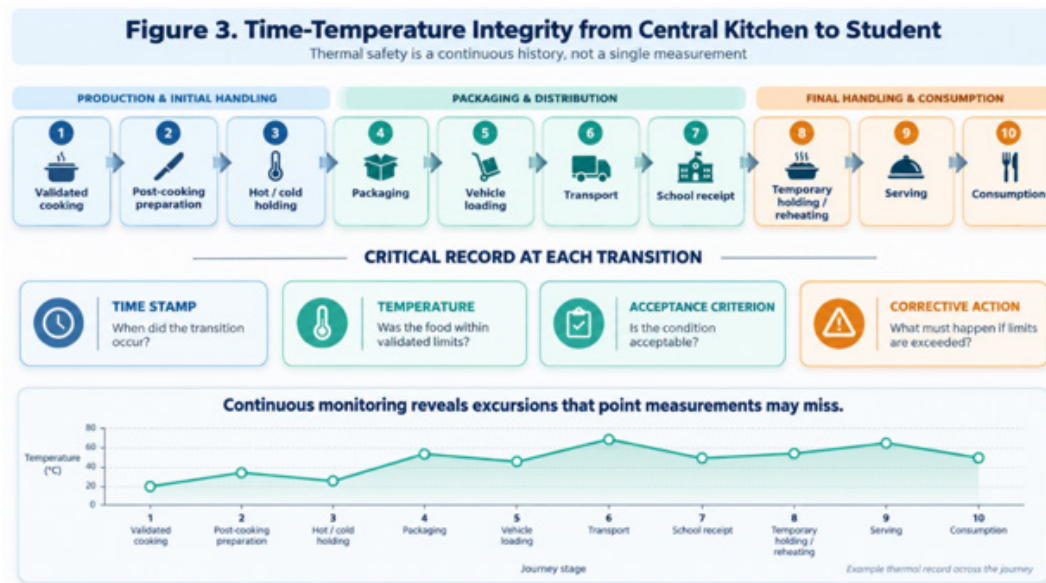


Figure 3: Time-Temperature Integrity from Central Kitchen to Student.

Figure 3 illustrates why an apparently acceptable arrival temperature may provide incomplete information if food experienced unsafe conditions earlier in the journey. Continuous or sufficiently frequent monitoring can reveal excursions that point measurements miss.

Theme 8: Traceability and Early Warning Limit Consequences after Prevention Fails

No preventive system can guarantee zero failures. Consequently, large school-meal networks require mechanisms to identify potentially affected schools and meals rapidly once an abnormal event is detected.

Traceability should link ingredients and suppliers to production dates, batches, menus, dispatch vehicles, schools, and consumption windows. This allows investigators to move both backward from cases to potential sources and forward from suspect materials to all potentially exposed schools. Digital traceability provides additional opportunities. Smart systems can integrate sensors, product identifiers, IoT devices, cloud computing, and analytical data, although data quality and interoperability remain critical [14,39,62,64]. More recent evidence shows that digital traceability is shifting toward combinations of RFID, IoT, artificial intelligence, blockchain, and integrated supply-chain software, while adoption remains constrained by technological, economic, interoperability, and organizational barriers [1]. An unusually relevant contemporary study comes from South Korea. Yeon and Smith (2026) [63] evaluated a school foodborne-illness early-warning system requiring schools to track foods and suppliers so that linked schools could be alerted when an outbreak occurred. Their analysis reported reductions in outbreak measures after implementation, although some comparisons with non-school settings offered weaker evidence, making the authors' results important but appropriately interpreted rather than treated as

universal causal proof.

Discussion and Analysis

School-Meal Contamination should be Treated as a System-Reliability Problem

The thematic synthesis indicates that large-scale school-meal safety is best understood through system reliability rather than isolated hygiene compliance. Unsafe outcomes can emerge even when most stages perform well because a single uncontrolled transition can undermine previous barriers. For analytical purposes, the relationship can be expressed conceptually as shown in Equation (1). The expression captures the multiplicative logic of risk amplification while deliberately avoiding the implication that the coefficients or exponents have been empirically calibrated.

$$R_{SM} \propto P_H \times P_P \times T_C \times B_S \times L_E \times D_R \times D_D \times V_C (1)$$

In Equation (1), RSM represents systemic school-meal safety risk, PH is the probability of hazard introduction, PP is persistence potential, TC is transfer or cross-contamination potential, BS is batch-scale amplification, LE is logistics and time-temperature exposure, DR is distribution reach, DD is detection delay, and VC represents the number and vulnerability of exposed consumers. These terms are conceptual dimensions rather than directly interchangeable physical units, so the expression should be interpreted as a systems framework rather than a numerical estimator. Equation (1) is not an empirically calibrated predictive equation. Its purpose is conceptual: it makes explicit that systemic consequence emerges through interacting amplification factors. Reducing any one factor can interrupt progression even when upstream contamination has already occurred. For example, a contaminated ingredient increases PH, but validated cooking may reduce its consequences. An environmental reservoir increases PP, yet effective sanitation and EMPs can interrupt persistence. Multi-

school distribution increases DR, but rapid traceability and early warning can reduce DD. This structure explains why food safety should be judged by overall system resilience rather than a single inspection score.

Prevention and Consequence Containment are Complementary

A useful distinction emerges between prevention and containment. Supplier assurance, hygienic design, cooking, sanitation, and temperature management aim to prevent unsafe meals from reaching students. Environmental monitoring, verification testing, and digital alarms identify deteriorating control. Traceability, early warning, incident response, and product withdrawal reduce consequences after prevention fails. Both capabilities are necessary in large-scale systems. Exclusive focus on prevention assumes the system will never fail, while exclusive focus on outbreak response accepts avoidable harm. A resilient architecture seeks both a low probability of occurrence and a small consequence conditional on occurrence. Evidence from the wider catering sector supports investment in structured food-safety policy. *Levy, et al., (2022) [27]* found that food-safety interventions across catering settings were associated with reductions in microbial contamination, although the evidence base remained heterogeneous. *Aik, et al., (2020) [3]* likewise found population-level benefits associated with formal food-safety management implementation in Singapore's catering sector, while *Tóth, et al., (2024) [55]* showed that external verification may detect operational weaknesses that internal self-checking overlooks.

HACCP is Necessary but cannot Operate Alone

HACCP remains foundational because it systematically identifies hazards, establishes control measures and critical limits, and defines monitoring and corrective action. However, many vulnerabilities in school meal systems occur outside narrowly defined critical control points. An environmental *Listeria* niche is partly a hygienic-design and sanitation issue. Undeclared allergens may arise through supplier changes or serving errors. Unsafe water may compromise cleaning and food preparation. Transport delays may invalidate otherwise controlled holding conditions. A school receiving team may accept food outside limits because no replacement meal exists. HACCP should therefore sit within a broader Food Safety Management System incorporating prerequisite programmes, procurement standards, sanitation, EMPs, equipment maintenance, allergen management, personnel competence, traceability, incident communication, and management review. The effectiveness of this architecture depends on verification as well as documentation, because internal self-assessment can overestimate conformity when hygiene, storage, cleaning, or disinfection practices are judged without independent challenge [55]. This systems perspective also avoids treating certification as synonymous with safety. A written plan has value only when operational behaviour matches documented controls. Verification must therefore include observation, record review, calibration, environmental data, deviation analysis, and corrective-action effectiveness.

Temperature Integrity should be Managed as a Continuous Chain

The evidence strongly supports treating the interval from cooking to consumption as one continuous thermal-control process. School-meal programmes should establish product-specific maximum and minimum temperatures and maximum elapsed times consistent with validated microbiological safety requirements. Continuous digital monitoring may improve visibility, but technological sophistication should reflect risk and operational feasibility. Where continuous sensing is unavailable, disciplined point measurements at defined transitions—end of cooking, dispatch, delivery, reheating, and serving—can still provide substantial protection if limits and corrective actions are explicit. Time-temperature monitoring should also be connected to traceability. A vehicle alarm has limited value if managers cannot determine which meals were affected. Conversely, detailed lot coding has limited preventive value if thermal excursions remain invisible.

Last-Mile Governance Deserves Equal Attention to Kitchen Governance

Central kitchens usually attract the greatest regulatory and managerial attention because they manufacture the food. Yet the last mile may contain poorly controlled transitions involving transport vehicles, unloading, temporary storage, reheating, classroom distribution, and final serving. An end-to-end governance model should therefore define responsibility at every handover. The sending kitchen should remain responsible for dispatch conditions, the logistics provider for transportation integrity, the receiving school for acceptance and local holding, and programme management for ensuring that no gaps arise between organizational boundaries. This is particularly important in systems involving contractors and subcontractors. Contractual performance metrics should include food-safety indicators rather than only delivery punctuality and cost. A delivery that arrives exactly on schedule but outside validated temperature limits cannot be considered successful.

Food-Safety Culture must Extend Across the Network

A central challenge in large programmes is that different actors may perceive food-safety responsibility differently. Suppliers may regard safety as the kitchen's responsibility, drivers may regard themselves only as transporters, schools may assume that food arriving from an approved kitchen is automatically safe. Such fragmentation creates responsibility gaps. Food-safety culture should instead be conceptualized at the network level. Every participant needs authority, knowledge, and responsibility to identify deviation and escalate concerns. Training is necessary but should be role-specific. Drivers need competence in temperature integrity, loading, contamination prevention, and deviation reporting. School staff need receiving and serving protocols. Kitchen personnel require detailed hygienic and process-control competence. Supervisors require trend analysis and corrective-action skills.

Technology should Strengthen Fundamentals Rather than Substitute for Them

Emerging technologies offer substantial opportunities but should be introduced according to the hierarchy of controls. A kitchen lacking reliable sanitation gains little from an advanced blockchain system. Similarly, IoT temperature monitoring cannot compensate for a vehicle that is physically incapable of maintaining required conditions. Rapid detection technologies can shorten information delays, predictive microbiology can support dynamic assessment, and digital traceability can accelerate containment. Cold plasma and high-pressure processing provide additional microbial-control options for appropriate foods [2,25,58]. Cold-plasma research demonstrates promising antimicrobial effects while also highlighting application-specific safety, sensory, and regulatory considerations. High-pressure processing likewise requires validation according to food matrix, organism, pressure, temperature, pH, and other characteristics rather than being assumed universally effective. The strategic priority should therefore be fit-for-risk technology rather than technology adoption for its own sake. Digital tools should be selected only when they reduce a clearly defined information, control, traceability, or response gap and when the organization has sufficient data quality, governance, maintenance, and human capability to act on their outputs [1].

Implications for Indonesia and Comparable Rapidly Scaling Systems

Indonesia offers an important contemporary context because school-meal delivery occurs across highly heterogeneous geographical, logistical, infrastructural, and institutional

environments. Earlier research on Indonesian school canteens already emphasized the need for stronger guidelines, capacity, monitoring, and stakeholder coordination [42]. More recent published commentary concerning Indonesia's expanded school-meal programme argues that outbreak surveillance and formal response protocols require strengthening as implementation scales. The reported events should be interpreted with caution because etiological confirmation was incomplete in many cases, nevertheless, the literature underscores the governance challenge created by rapid scale-up [50]. The practical implication is that safety capacity should grow at least as fast as meal-production capacity. Adding kitchens and meals without proportional growth in trained personnel, laboratory capacity, environmental monitoring, temperature-control infrastructure, traceability, and outbreak-response systems can widen the gap between operational scale and control capability. This principle extends beyond Indonesia. Any rapidly expanding school-feeding system should prioritize foundational infrastructure before advanced technological layers. Clean water, hygienic facility design, appropriate equipment, calibrated temperature measurement, standardized supplier controls, sanitation, employee competence, and clear escalation authority should precede or accompany more sophisticated data systems.

Proposed Twelve-Layer Defence-in-Depth Model

The literature synthesis supports a twelve-layer architecture extending across the complete system. Its purpose is to make redundancy explicit so that a failure at one barrier can be detected, contained, or compensated for by another barrier before students are exposed.

Figure 4. Twelve-Layer Defence-in-Depth Architecture for School Meal Safety

Multiple independent barriers prevent one local failure from becoming a system-wide event



Figure 4: Twelve-Layer Defence-in-Depth Architecture for School Meal Safety.

Figure 4 organizes these controls into a defence-in-depth model. The layers are deliberately redundant because high-reliability systems do not assume that every preventive measure will function perfectly in every meal-production cycle.

The advantage of the twelve-layer model is that no single control is treated as infallible. If supplier controls fail, cooking may intervene. If cooking is insufficient, process monitoring should identify the deviation. If contamination occurs after cooking, environmental controls may detect the source. If unsafe meals enter distribution, traceability and early warning can reduce downstream exposure.

Digital Early-Warning Architecture

The growing availability of sensors, laboratory information systems, distribution records, digital attendance data, and complaint systems creates opportunities for faster anomaly detection. However, data integration must remain proportionate to privacy, governance, accuracy, and operational needs.

Figure 5 shows how multiple information streams can be integrated without assuming that artificial intelligence replaces professional judgement. The architecture emphasizes that automated detection and prioritization should culminate in accountable human review, coordinated intervention, and feedback into prevention.

Figure 5 emphasizes that the value of digitalization lies in reducing the interval between abnormal conditions and action. The South Korean early-warning study provides particularly relevant empirical evidence that structured information sharing may reduce aspects of school foodborne-illness burden [63]. Recent traceability research further indicates that integrated digital systems can improve transparency, monitoring, and logistics, but their effectiveness depends on interoperability, organizational readiness, and disciplined data governance [1].

Conclusion and Recommendations

Large-scale school-meal provision can deliver substantial nutritional and social benefits, but scale changes the consequences of food-safety failure. The defining challenge is not that centralized kitchens necessarily generate different hazards, rather, large production batches, common suppliers, shared equipment, extended holding, transportation, and simultaneous multi-school distribution create pathways through which one failure can affect many students. The review identifies biological contamination as the principal driver of acute foodborne illness while recognizing the importance of allergens, mycotoxins, chemical migrants, persistent environmental contaminants, and emerging hazards. These risk categories require different controls and should not be collapsed into a single generic notion of food contamination. Food safety should consequently be managed as an end-to-end property of the complete school-meal system. Supplier qualification, receiving, storage, preparation, cooking, holding, packaging, transportation, school receiving, reheating, serving, and consumption form one connected safety chain. Responsibility cannot terminate when

food leaves the central kitchen. Particular priority should be assigned to time-temperature integrity, raw-to-cooked separation, post-cooking hygiene, environmental monitoring, water quality, transport controls, and school-level receiving verification. These areas repeatedly emerge as mechanisms through which otherwise controlled food can become unsafe. HACCP and formal Food Safety Management Systems should remain foundational but should operate within a broader defence-in-depth architecture. Their effectiveness depends on adequate prerequisites, sanitation, environmental monitoring, supplier management, staff competence, traceability, leadership, and a culture in which workers are encouraged to identify and report deviations.

School-meal systems should also maintain consequence-containment capacity. Rapid traceability, communication mechanisms, retained information on production and delivery, early-warning surveillance, predefined outbreak protocols, and root-cause investigation can substantially reduce the number of students exposed when preventive controls fail. Technology can strengthen these protections but should follow rather than replace fundamental food-safety infrastructure. Continuous temperature sensors, rapid diagnostics, predictive microbiology, digital traceability, and integrated data systems are most valuable when embedded within reliable processes and supported by competent human decision-makers. For rapidly expanding programmes, food-safety capacity should grow in parallel with production capacity. Expansion of meal numbers should therefore be accompanied by proportional strengthening of trained personnel, infrastructure, sanitation capability, laboratory networks, transport controls, traceability, surveillance, and emergency response. The overarching recommendation is to move from a narrow “safe kitchen” paradigm toward an “end-to-end safe school-meal system” paradigm. In this model, every handover is treated as a potential control point, every deviation can be escalated, and multiple barriers prevent one local failure from becoming a large-scale student health event.

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Conflict of Interest

None.

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