Identification of critical control points for fruit fly infestation in the export supply chain of *Salacca zalacca* cv. 'Pondoh'

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Abstract. Fruit fly infestation (*Bactrocera spp*.) remains a major phytosanitary challenge in tropical fruit exports. This study assessed observable fruit fly infestation incidence along the export-oriented supply chain of *Salacca zalacca* var. pondoh using a process-oriented approach integrating SCOR-based material flow mapping, descriptive critical control point (CCP) identification, and latent infestation observation. Fruit samples were collected at the farm level, farmer group aggregation (Sortation I), and packing house handling (Sortation II), and stored under ambient conditions for 14 days to allow infestation expression. Infestation incidence differed across supply-chain stages, with the highest occurrence observed at the farmer group level, lower incidence at the farm level, and no infestation detected in packing house samples under the applied observation protocol. These findings indicate that infestation expression varied by handling stage and highlight aggregation points as priority stages for postharvest pest risk management in export-oriented salak supply chains.

1 Introduction

Fruit flies (*Bactrocera spp.*) are among the most economically significant quarantine pests affecting tropical fruit exports, posing substantial risks to market access under increasingly stringent phytosanitary regulations. Infestation not only reduces fruit quality and yield but also leads to shipment rejection and trade restrictions, thereby undermining the reliability of export-oriented supply chains [1,2].

Salacca zalacca var. pondoh, commonly known as salak pondoh**,** is a high-value tropical fruit native to Indonesia and increasingly targeted for international markets, particularly East Asia. Despite the implementation of Good Agricultural Practices (GAP) and standardized postharvest handling protocols, fruit fly infestation remains a persistent challenge. Most existing studies emphasize orchard-based management, focusing on monitoring, trapping, and sanitation practices at the production stage [3,4]. Such approaches implicitly assume that infestation risk is generated and controlled primarily at the farm level.

Recent advances in agri-food supply chain research, however, suggest that biological hazards are strongly process-driven and may intensify at specific operational stages rather

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than remaining confined to the production site. Aggregation, prolonged exposure, and variability in handling practices have been shown to amplify postharvest risks within fresh produce supply chains [5]. In tropical fruit exports, material flow analysis combined with critical control point (CCP) identification has proven effective in revealing intermediate postharvest stages as major vulnerability points for disease and pest development [6]. Nevertheless, comparable process-oriented assessments remain scarce for salak pondoh, particularly with respect to fruit fly infestation.

Another critical limitation in current risk assessment practices is the reliance on visual inspection at harvest or shipment, which often fails to detect latent infestation. Eggs and early larval stages of Bactrocera spp. may remain asymptomatic during early handling and only become apparent during storage, resulting in systematic underestimation of infestation risk [2,7]. Consequently, evaluations that overlook postharvest infestation dynamics may provide a false sense of phytosanitary security.

To address these gaps, this study adopts a process-oriented supply chain perspective by integrating the Supply Chain Operations Reference (SCOR) model, CCP reminder-based risk analysis, and biological validation through latent infestation observation. By tracing material flow from the farm level, through farmer group aggregation, to the packing house, infestation risk is examined as an emergent outcome of operational interactions along the supply chain.

The objectives of this study were to: (i) quantify fruit fly infestation incidence across key stages of the export-oriented S. zalacca var. pondoh supply chain; (ii) identify critical control points (CCPs) associated with infestation risk using a SCOR-based framework; and (iii) assess the role of GAP compliance in shaping infestation outcomes. By shifting the analytical focus from orchard-centric control to stage-specific risk management, this study contributes new insights into postharvest pest control and supports the development of more resilient tropical fruit export systems.

2 Materials and methods

2.1 Study design and analytical framework

This study employed a process-oriented postharvest risk assessment design to evaluate fruit fly infestation along an export-oriented salak pondoh supply chain. The analytical framework integrated material flow analysis, Supply Chain Operations Reference (SCOR) model, and critical control point (CCP) identification to capture infestation risk as an outcome of operational interactions rather than isolated production activities.

Material flow mapping was conducted following the reference approach for agri-food supply chain risk analysis proposed by Olsen and Aschan [5]. The CCP-based analytical logic was adapted from Matulaprungsan et al. [6], which demonstrated the effectiveness of combining material flow observation with postharvest biological risk assessment in tropical fruit export systems. The SCOR model was applied as a conceptual structure to classify operational stages into Source, Make, and Deliver processes [9].

2.2 Supply chain stages and observation units

Based on the SCOR framework, the salak pondoh export supply chain was divided into three operational stages that served as observation units throughout the study:

1) Farm level (Source): freshly harvested fruits prior to transportation;
2) Farmer group level (Sortation I; Make): fruits undergoing aggregation and initial manual sorting;

3) Packing house level (Sortation II; Make–Deliver): fruits after final sorting, sanitation, and preparation for export.

These stages represent distinct handling environments characterized by differences in exposure duration, sanitation control, and aggregation intensity, which are known to influence postharvest pest risk accumulation [5,6].

2.3 Study area and period

The study was conducted in Turi District, Sleman Regency, Special Region of Yogyakarta, Indonesia. Field observations were carried out at salak pondoh orchards and farmer group collection points supplying CV. Mitra Turindo, while postharvest handling observations and final sampling were conducted at the company's packing house. Laboratory observations were performed at the Postharvest Laboratory and Plant Protection Laboratory, Universitas Muhammadiyah Yogyakarta.

2.4 Sampling design

Sampling was designed to allow comparative analysis of infestation incidence across supply-chain stages. Sample size determination followed the approach proposed by Isaac and Michael to ensure representativeness of the observed population.

The sampling allocation was as follows:

- Farm level: 320 fruits, consisting of 20 fruits collected from each of 16 farmers;
- Farmer group level (Sortation I): 67 fruits randomly sampled during aggregation;
- Packing house level (Sortation II): 67 fruits sampled after final sorting.

Fruit samples collected at different supply-chain stages were obtained from different harvest batches and were not tracked as a single continuous lot through the supply chain. Consequently, comparisons of infestation incidence among stages represent descriptive stage-level observations rather than causal effects of specific practices. Only fruits that visually met export quality standards at the time of sampling were included to ensure that observed infestation represented latent infestation rather than pre-sorting rejection.

2.5 Observation of fruit fly infestation development

To allow expression of latent fruit fly infestation, all sampled fruits were stored under ambient laboratory conditions (25–28 °C, relative humidity approximately 65–80%) without chemical treatment. Fruits were placed individually in ventilated plastic containers and observed daily for 14 days. The 14-day observation period was selected based on previous studies indicating that this duration is sufficient for symptom expression of latent infestation in tropical fruits [2,7].

Observation focused on external and internal infestation indicators, including oviposition puncture marks, tissue softening, discoloration, larval or pupal emergence, and off-odor development. Infestation was confirmed by direct visual detection of larvae or pupae and morphological characteristics consistent with *Bactrocera* spp., following established postharvest observation protocols [1,2].

2.6 GAP compliance assessment

Good Agricultural Practices (GAP) compliance was evaluated as an explanatory variable influencing infestation outcomes. Assessment criteria were based on internationally recognized GAP guidelines for horticultural products [8]. GAP compliance was assessed at the farmer-group level as a contextual indicator of prevailing production and handling practices. Fruit samples used for infestation observation were not traceable to individual farmer GAP scores beyond the farm-level sampling stage. Therefore, GAP compliance data were not subjected to statistical association analysis with fruit-level infestation outcomes and were used solely to support descriptive interpretation. A structured questionnaire and direct field observation were administered to 30 farmers from three farmer groups. Evaluated components included orchard sanitation, fruit thinning and residue disposal, pest control practices, and harvest and postharvest handling procedures. GAP compliance was expressed as percentage conformity for each practice category.

2.7 Variables and measurements

The primary response variable was fruit fly infestation incidence (%), calculated using the following formula: "Infestation incidence (%)"=n/N×100

where n is the number of infested fruits and N is the total number of observed fruits at each supply-chain stage.

Secondary variables included qualitative descriptions of postharvest damage symptoms and developmental stages of infestation, which supported biological interpretation of infestation dynamics [1,2].

2.8 Data analysis and identification of critical control points

Data were analyzed using descriptive statistical methods, including frequency distribution and percentage comparison, to evaluate differences in infestation incidence across supply-chain stages. In this study, critical control points (CCPs) were identified using a rule-based descriptive approach. A supply-chain stage was designated as a CCP when two conditions were met simultaneously: (i) observable fruit fly infestation incidence was higher than that of adjacent stages, and (ii) the stage involved handling or environmental conditions known from the literature to facilitate fruit fly oviposition or development. No composite risk score or probabilistic weighting was applied. Accordingly, data analysis focused on descriptive comparison of infestation incidence across operational stages without inferential statistical testing.

The integration of infestation data with SCOR-based operational mapping enabled identification of priority intervention stages for postharvest pest risk mitigation, consistent with supply chain risk management principles [5,6,9]. It is important to note that fruit samples collected at different supply-chain stages were not tracked as a single continuous lot. Therefore, comparisons among stages are descriptive in nature and do not imply causal relationships between specific practices and infestation outcomes.

3 Results and discussion

3.1 Temporal and Stage-Specific Dynamics of Fruit Fly Infestation

The following results describe stage-specific differences in observable infestation incidence without inferring direct causal mechanisms. The temporal development of fruit fly infestation during ambient storage revealed clear stage-specific patterns across the export-oriented salak pondoh supply chain (Table 1). No infestation was detected at the packing house level throughout the 15-day observation period, whereas infestation at the farmer group level became evident from day 6 onward and increased steadily to 15% by day 15. In contrast, infestation at the farm level appeared later and remained lower, reaching 6% at day 15.

These results confirm that fruit fly infestation in Salacca zalacca is predominantly latent at harvest, becoming detectable only after storage. Similar latency has been reported for Bactrocera spp. in other tropical fruits, where eggs and early larval stages remain asymptomatic during initial handling and only manifest under favorable postharvest conditions [1,2]. Importantly, the highest infestation intensity at the farmer group level indicates that infestation risk is not linearly inherited from orchards, but instead amplified at intermediate handling stages.

Table 1. Temporal fruit fly infestation incidence across supply-chain stages

Locations	Fruit infestations (%)					
	0	3	6	9	12	15
Packing house	0	0	0	0	0	0
Farmer group	0	0	2	5	9	15
Farmer	0	0	0	0	2	6

Table 2. GAP compliance in Salacca production and handling

	GAP practices in Salacca production	compliance	non-compliance
Pruning	1. infiltration pits in the field	93%	7%
	2. pile the pruning into the pits	90%	10%
Fertilization	1. Use organic fertilizer	100%	0%
	2. Collect thinning results for fertilizer application	73%	27%
	3. Fertilize at the beginning and end of the rainy season	87%	13%
Thinning	1. Thin the fruit	100%	0%
	2. Collect the thinning results	73%	27%
Plant Protection	1. Use of natural enemies	60%	40%
	2. Mechanical control	87%	13%
	3. Use of biological/botanical pesticides	67%	33%
Harvesting	1. Pick and select according to export standards	100%	0%
	2. Collect the harvest in baskets	100%	0%
	3. Store the harvest in a clean place	100%	0%
Postharvest	1. Sorting/grading	100%	0%
	2. Labeling the packaging	100%	0%

This finding aligns with supply chain–based risk assessments in tropical fruit exports, which have demonstrated that aggregation points often function as biological risk multipliers due to extended exposure time and mixed fruit origins [3,4]. Thus, the farmer group level represents a critical stage where infestation risk escalates beyond that observed at the production site.

3.2 GAP Compliance Patterns and Infestation Outcomes

The following interpretation considers GAP compliance as a descriptive contextual factor rather than a statistically tested determinant of fruit-level infestation. The observed infestation dynamics can be explained by heterogeneous GAP compliance across production and handling stages (Table 2). Downstream practices, including harvesting and postharvest handling, showed full compliance (100%), covering selection according to export standards, clean storage, sorting, and labeling. This strict compliance is consistent with the absence of infestation at the packing house level, supporting evidence that well-managed postharvest environments can effectively intercept infestation pathways [5].

Table 3. Identified Critical Control Points (CCPs) along the export-oriented salak pondoh supply chain

Supply-chain stage (SCOR)	Critical activity	CCP justification	Operational implication
Farm level (Source)	Improper disposal of thinning residues	Presence of unmanaged fruit residues associated with known oviposition substrates	Sustains local infestation reservoirs
Transport to farmer group (Source–Make)	Transport without protective netting	Exposure during transport coincides with early infestation expression	Increases likelihood of infestation during aggregation
Farmer group sorting (Make)	Open-air sorting and aggregation	Highest observed infestation incidence among stages	Priority intervention point
Packing house (Deliver)	Controlled sorting and sanitation	No infestation detected under observation protocol	Effective final handling control

In contrast, upstream practices exhibited partial compliance, particularly in thinning residue management and plant protection. Although fruit thinning itself was universally practiced, only 73% of farmers collected thinning residues, leaving over one-quarter of orchards with unmanaged fruit waste. Discarded thinning residues are well recognized as key oviposition substrates for fruit flies, sustaining local populations and increasing infestation pressure [6].

Plant protection practices showed the lowest compliance, especially in the use of natural enemies (60%) and biological or botanical pesticides (67%). Partial adoption of biologically based control strategies limits area-wide suppression of Bactrocera populations and has been shown to reduce the effectiveness of integrated pest management programs [7,8]. These upstream compliance gaps provide a biological explanation for why infestation pressure persisted and later manifested during aggregation.

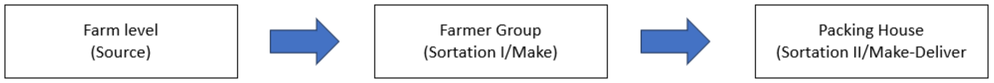

Figure 1. SCOR-based material flow of export-oriented salak pondoh supply chain.

3.3 Critical Control Points along the Supply Chain

In this study, critical control points are defined operationally as stages where higher infestation incidence was observed concurrently with specific handling conditions, rather than as statistically validated risk determinants. By integrating infestation data with GAP compliance patterns, several critical control points (CCPs) were identified. Improper disposal of thinning residues emerged as a primary CCP at the farm level, functioning as an infestation initiator. During transport from farms to farmer groups, the absence of protective netting further increased fruit exposure to oviposition. Based on the applied descriptive criteria, the farmer group sorting stage met the conditions for designation as a critical control point due to its higher observed infestation incidence and open-air handling practices. Comparable CCPs have been reported in export-oriented mango and citrus supply chains, where open-air aggregation and sorting significantly increased pest and disease risk despite upstream control efforts [3,9]. These findings reinforce the conclusion that infestation risk is concentrated at specific operational stages, rather than uniformly distributed along the supply chain. The CCPs identified in this study should be interpreted as descriptive priority points rather than quantitatively ranked risk levels, as no formal risk-scoring was applied.

3.4 SCOR-Based Interpretation of Risk Accumulation

The SCOR framework provides a structured interpretation of infestation risk accumulation. At the Plan level, standard operating procedures were available but not consistently implemented, particularly for residue management and transport protection. Within the Source process, sourcing and transport from farms to farmer groups represented vulnerable stages due to exposure and partial GAP compliance. The Make process—specifically thinning and sorting at the farmer group level—constituted the highest-risk CCP, where biological and operational factors converged. In contrast, the Deliver process at the packing house was well controlled, as reflected by zero infestation. The Return dimension highlights the potential for export rejection if infestation is detected, emphasizing the economic consequences of upstream control failures [10].

3.5 Integrated Interpretation and Novel Contribution

Taken together, these results demonstrate that fruit fly infestation in export-oriented Salacca zalacca is process-specific, cumulative, and strongly shaped by intermediate handling practices. While high compliance at downstream stages can effectively block infestation from entering export channels, partial compliance upstream is sufficient to sustain infestation pressure that manifests during aggregation.

This study advances current understanding by demonstrating that GAP operates as a gradient risk modifier rather than a binary standard, and by identifying the farmer group aggregation stage as the most effective leverage point for infestation risk reduction. These findings suggest that targeted interventions at aggregation and residue management stages may yield greater phytosanitary benefits than orchard-level control alone. This study is limited by its descriptive design and the absence of lot-level traceability across supply-chain stages. Consequently, observed associations between handling practices and infestation outcomes should be interpreted as indicative rather than causal.

4 Conclusion

This study demonstrates that observable fruit fly infestation incidence in export-oriented Salacca zalacca var. pondoh varied across supply-chain stages. The highest infestation incidence was observed at the farmer group aggregation stage, while no infestation was detected at the packing house stage under the conditions of this study. These results suggest that intermediate handling and aggregation stages represent priority points for targeted postharvest pest risk management. Given the descriptive nature of the study and the absence of lot-level traceability, the observed patterns should be interpreted as indicative rather than causal. Future studies incorporating batch tracking and quantitative risk modeling are needed to further validate stage-specific infestation dynamics.

References

1. R.I. Vargas, J.C. Piñero, L. Leblanc, An overview of pest species of *Bactrocera* fruit flies (Diptera: Tephritidae) and the integration of biopesticides with other biological approaches for their management. Insects 6, 297–318 (2015). https://doi.org/10.3390/insects6020297
2. M.K. Schutze, N. Aketarawong, W. Amornsak, K.F. Armstrong, A.A. Augustinos, N. Barr, et al., Synonymization of key pest species within the Bactrocera dorsalis species complex (Diptera: Tephritidae): Taxonomic changes based on integrative morphological, molecular, cytogenetic, behavioural and chemoecological data. Syst. Entomol. 40, 456–471 (2015). https://doi.org/10.1111/syen.12113
3. A. Susanto, T. Kustiariyah, Y.A. Trisyono, Population dynamics of fruit flies (Bactrocera spp.) on tropical fruit orchards in Indonesia. Biodiversitas 18, 325–331 (2017). https://doi.org/10.13057/biodiv/d180142
4. S. Ekesi, S.A. Mohamed, M. De Meyer, Fruit fly pests and their management in Africa: Recent advances and future directions. CAB Rev. 11, 1–14 (2016). https://doi.org/10.1079/PAVSNNR201611033
5. P. Olsen, M. Aschan, Reference method for analysing material flow, information flow and information loss in food supply chains. Trends Food Sci. Technol. 21, 313–320 (2010). https://doi.org/10.1016/j.tifs.2009.07.003
6. B. Matulaprungsan, F. Tanaka, S. Ohashi, N. Khaeophimai, Analysis of critical control points of post-harvest diseases in the material flow of 'Nam Dok Mai' mango exported to Japan. Agriculture 9, 200 (2019). https://doi.org/10.3390/agriculture9090200
7. L.F. Arauz, Mango anthracnose: Economic impact and current options for integrated management. Plant Dis. 84, 600–611 (2000). https://doi.org/10.1094/PDIS.2000.84.6.600
8. Food and Agriculture Organization of the United Nations, Good Agricultural Practices for Horticultural Products (FAO, Rome, 2020).
9. P. Bolstorff, R. Rosenbaum, Supply Chain Excellence: A Handbook for Dramatic Improvement Using the SCOR Model (AMACOM, New York, 2007).
10. Y. Qin, D.R. Paini, C. Wang, Y. Fang, Z. Li, Global establishment risk of economically important fruit fly species (Tephritidae). PLoS One 10, e0116424 (2015). https://doi.org/10.1371/journal.pone.0116424