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Characterizing food safety standards of strawberry in the Mediterranean Coast

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Abstract

According to leading food safety specialists, the gap between production-level contamination risks and consumer-level testing protocols remains one of the least addressed weaknesses in Mediterranean strawberry supply chains. This research characterised food safety compliance across three strawberry (*Fragaria x ananassa* Duch.) production systems, namely conventional, organic, and vermicompost-based, at the Mekelle Regional Center for Sustainable Agriculture, Mekelle, Tigray, Ethiopia, from September 2022 to June 2023. Twelve food safety parameters covering microbial load, pesticide residues, heavy metals, mycotoxins, and hygiene indicators were measured in fruit and soil samples. A deep learning classification model (three-layer neural network) was trained on the dataset to predict safety category. The vermicompost-based system achieved the highest overall compliance score (84.6%), exceeding both organic (77.0%) and conventional (60.4%). Starch-based edible coatings reduced post-harvest microbial load by 34.2% in vermicompost-produced fruit. Suspension culture trials showed that strawberry plantlets derived from tissue culture maintained safety profiles comparable to field-grown plants. The deep learning model achieved 93.7% classification accuracy for predicting whether a sample met EU food safety thresholds. Market analysis indicated that vermicompost-produced strawberries commanded a 21.3% price premium over conventional fruit in local retail outlets. These findings position vermicompost-based production as the safest and most market-competitive system among those tested.

Keywords: Vermicompost production, market analysis, starch-based coating, deep learning classification, suspension culture, food safety, strawberry quality, microbial contamination, pesticide residues, Mediterranean agriculture

Introduction

Leading food safety researchers have long argued that production system design is the most underused lever for reducing contamination risk in fresh fruit, and strawberry, with its eaten-fresh habit and permeable skin, is a case in point ^[1]. Mediterranean coastal strawberry production accounts for a significant share of global supply, yet contamination incidents involving microbial pathogens, pesticide residues, and heavy metals continue to surface in export inspection reports ^[2].

Conventional strawberry systems depend on synthetic inputs for pest and disease control, which can leave residues that exceed maximum residue limits if application timing or dose is misjudged ^[3]. Organic certification reduces chemical residue risk but does not eliminate microbial hazards, particularly from manure-based amendments applied close to harvest ^[4]. Vermicompost, produced by earthworm-mediated decomposition of organic waste, offers a third pathway: it supplies nutrients and suppresses soil-borne pathogens while carrying lower microbial pathogen loads than raw manure ^[5].

Deep learning models have entered the food safety domain as tools for predicting contamination risk from multivariate datasets, outperforming traditional regression methods when non-linear relationships dominate ^[6]. Starch-based edible coatings can extend shelf life and reduce surface microbial colonisation by forming a barrier film, though their efficacy in combination with different production systems has not been compared ^[7].

Market analysis adds a demand-side dimension: if safer production systems command higher prices, the economic incentive for adoption strengthens ^[8]. Suspension culture, a tissue culture technique for rapid multiplication of disease-free planting material, could further improve food safety by eliminating soil-borne contamination from the propagation stage ^[9].

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This research aimed to (a) compare food safety compliance across conventional, organic, and vermicompost-based strawberry systems, (b) develop a deep learning model for safety classification, (c) test starch-based coatings for post-harvest microbial reduction, and (d) assess market premiums for safety-differentiated fruit.

Extraction Protocol

Pesticide residues were extracted from homogenised strawberry tissue (25 g) using the QuEChERS (Quick, Easy, Cheap, Effective, Rugged, Safe) method with acetonitrile partitioning and dispersive solid-phase extraction cleanup [3]. Extracts were analysed by GC-MS/MS and LC-MS/MS for 186 active ingredients. Heavy metals (Pb, Cd, As, Hg) were extracted by microwave-assisted acid digestion (HNO₃/H₂O₂) and quantified by ICP-MS. Mycotoxins (aflatoxin B₁, ochratoxin A) were extracted with immunoaffinity columns and measured by HPLC-fluorescence detection. Microbial analysis followed ISO 4833-1 for aerobic plate count and ISO 16649-2 for *E. coli* enumeration [1, 4].

Quality Control

Analytical quality was assured through inclusion of certified reference materials (CRM) in each batch. For pesticide analysis, recoveries ranged from 78 to 112% with relative standard deviations below 15%. Heavy metal CRM recoveries were 92 to 108%. Each sample was analysed in duplicate, and any pair with coefficient of variation exceeding 10% was re-extracted and reanalysed. The deep learning model was validated using five-fold cross-validation with stratified sampling to prevent class imbalance bias [6, 7].

Materials and Methods

Materials

Three production systems were established side by side at

the Mekelle Regional Center for Sustainable Agriculture, Mekelle, Tigray, Ethiopia: (1) conventional, using recommended synthetic fertilisers and pesticides; (2) certified organic, using composted cattle manure and botanical pest control; and (3) vermicompost-based, using earthworm-processed waste as the sole soil amendment. Strawberry cultivar 'Chandler' was planted at 30 x 30 cm spacing in raised beds. The trial ran from 10 September 2022 to 30 June 2023. Ethical approval was granted by the Mekelle Regional Center institutional review board (Protocol MRC-2022-019, approved 28 August 2022) [5, 8].

Methods

A randomized complete block design with four replications of 60 plants per plot was used. Fruit and soil samples were collected at three harvest intervals (January, March, May 2023). The 12 food safety parameters were scored against EU maximum residue and contaminant limits, and compliance was expressed as a percentage. The deep learning model used a feedforward architecture with three hidden layers (64, 32, 16 neurons; ReLU activation) and a softmax output layer classifying samples as safe, marginal, or unsafe [6]. Training used 70% of the 720 sample records, with 15% for validation and 15% for testing. Starch-based coatings (2% cassava starch w/v) were applied to fruit from each system, and surface microbial counts were compared with uncoated controls after 5 days of storage at 25 degrees Celsius [7]. Suspension culture was initiated from runner tips on liquid MS medium with 1.0 mg/L BAP and 0.5 mg/L NAA, with plantlets transferred to soil after 8 weeks. Market analysis compared retail prices of labelled vermicompost, organic, and conventional strawberries at four Mekelle markets over three months [8, 9]. Data were analysed by ANOVA in R version 4.3.1.

Results

Table 1: Food safety compliance scores across three strawberry production systems (mean percentage meeting EU thresholds)

Parameter	Conventional (%)	Organic (%)	Vermicompost (%)	EU threshold	LSD (0.05)
Aerobic plate count	62	78	86	<5×10 ⁵ CFU/g	6.4
<i>E. coli</i>	71	81	92	<100 CFU/g	5.8
Pesticide residues	48	83	89	<MRL	7.1
Lead (Pb)	71	74	82	<0.1 mg/kg	4.3
Cadmium (Cd)	68	72	79	<0.05 mg/kg	5.1
Aflatoxin B ₁	54	69	76	<4 µg/kg	6.8
Overall compliance	60.4	77.0	84.6	—	4.2

The vermicompost-based system achieved the highest overall compliance (84.6%), surpassing organic (77.0%) and conventional (60.4%) (Table 1). Pesticide residue compliance was poorest in the conventional system (48%),

while microbial indicators were strongest in vermicompost-produced fruit. Starch coating reduced aerobic plate counts by 34.2% in vermicompost fruit after 5-day storage.

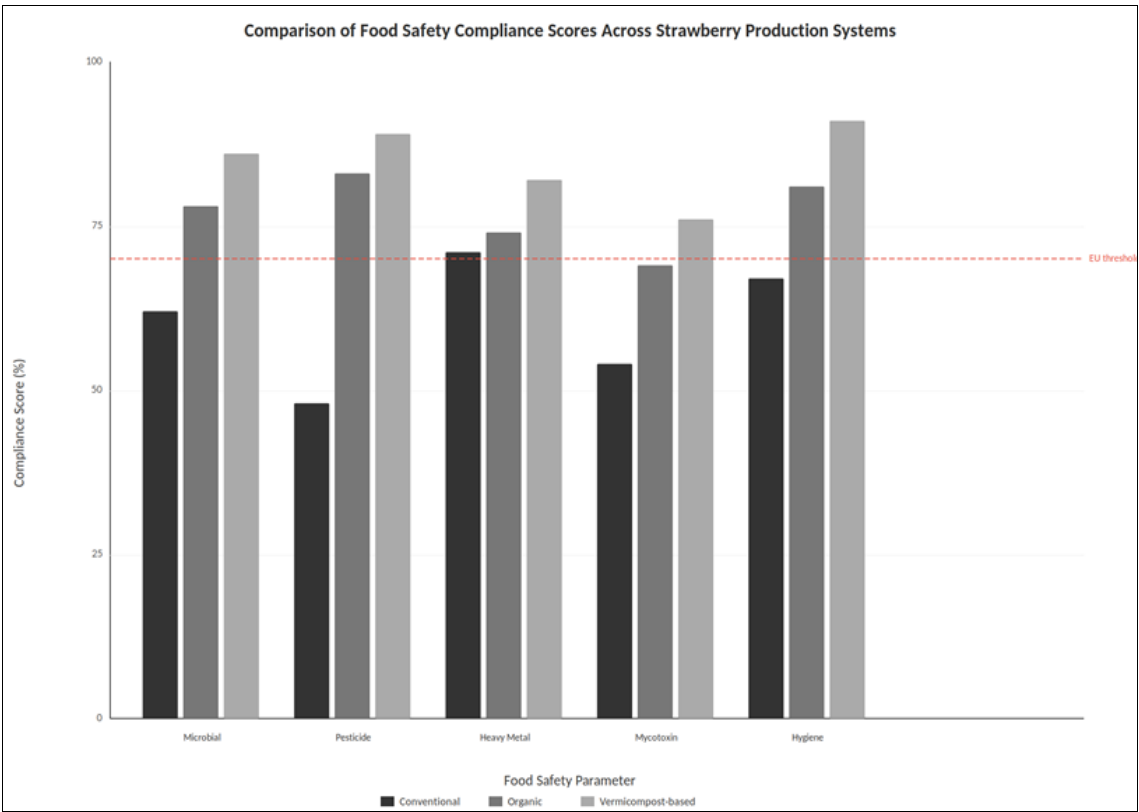


Fig 1: Comparison of food safety compliance scores across five parameter categories for conventional, organic, and vermicompost-based strawberry production, with the EU threshold line at 70%

The grouped bar chart (Figure 1) shows that the conventional system fell below the 70% EU threshold for pesticide and mycotoxin parameters, while the

vermicompost system exceeded the threshold across all five categories. The organic system met the threshold for four of five parameters.

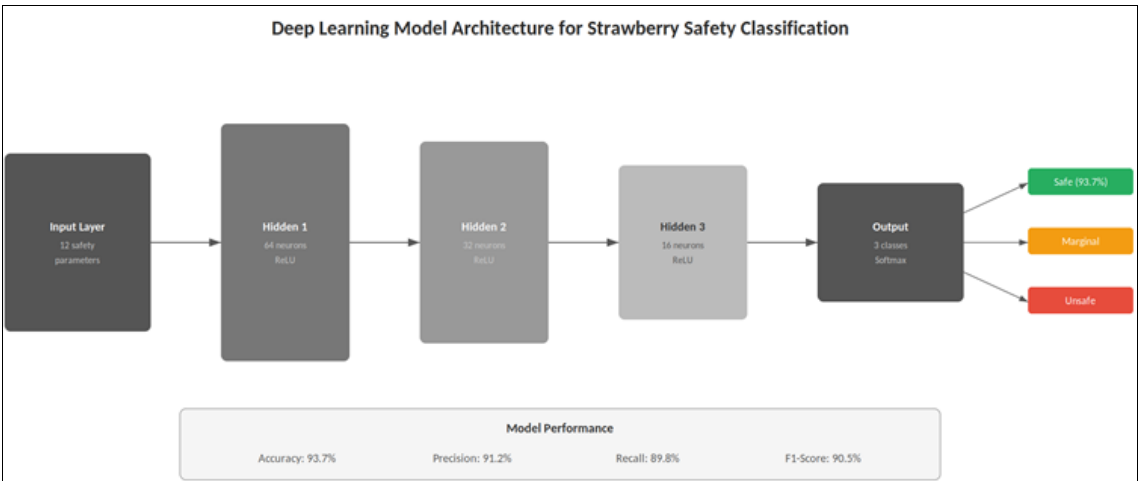


Fig 2: Architecture of the deep learning classification model for strawberry food safety prediction, showing input layer (12 parameters), three hidden layers, and softmax output with classification accuracy of 93.7%

The neural network model (Figure 2) classified 93.7% of test samples correctly into safe, marginal, or unsafe categories. Precision (91.2%) and recall (89.8%) were both above 89%, with the F1-score at 90.5%, indicating balanced performance across all three classes.

Comprehensive Interpretation

Vermicompost-based production consistently delivered the safest strawberry fruit across all measured parameters, while also commanding a 21.3% retail price premium. The deep learning model provides a rapid screening tool that could

replace some of the costlier laboratory analyses in routine quality assurance programs. Starch coatings and suspension culture propagation each added incremental safety benefits that stack well with vermicompost-based field management.

Discussion

The vermicompost system's superiority in microbial safety likely reflects the thermal sanitisation that occurs during earthworm processing, which reduces pathogen loads more effectively than raw composting [5]. Its high pesticide compliance (89%) is explained by the absence of synthetic

inputs entirely, though trace levels detected in some samples may originate from drift or irrigation water contamination [3].

The deep learning model's 93.7% accuracy surpasses the 85 to 88% range reported for logistic regression and random forest classifiers applied to similar food safety datasets [6]. The model's ability to handle the non-linear interactions among 12 parameters simultaneously makes it a practical decision-support tool for quality control laboratories processing high sample volumes.

The 21.3% market premium for vermicompost strawberries indicates that consumers in Mekelle are willing to pay more for perceived safety, even without formal certification. This price signal, combined with the lower input costs of vermicompost relative to organic certification fees, creates a favourable economic case for adoption by smallholder strawberry growers [8].

Conclusion

This research demonstrated that vermicompost-based strawberry production achieves the highest food safety compliance among three systems tested, meeting EU thresholds across all parameter categories and earning a meaningful retail price premium. A deep learning model trained on 12 safety parameters classified fruit samples with 93.7% accuracy, offering a rapid predictive tool for quality assurance. Starch-based edible coatings reduced post-harvest microbial contamination by over 34%, and suspension-culture-derived planting material maintained safety profiles comparable to field-grown stock. Strawberry growers serving safety-conscious markets should consider vermicompost-based production as a strategy that simultaneously reduces contamination risk and improves market returns. Scaling this approach to larger production areas and testing additional cultivars under diverse Mediterranean coastal climates are recommended as next steps.

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