



Life cycle assessment of a major tropical fruit—sugar apple (*Annona squamosa*) under different farming systems in Taiwan

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Abstract

Purpose This study quantifies the environmental impacts of sugar apple production (*Annona squamosa*) under different farming systems in Taitung, Taiwan, with the inclusion of organically certified materials into the life cycle inventory. It identifies process- and stage-level hotspots, determines the *dominant impact category (DIC)* for each orchard, and examines how cultivation practices influence yield and environmental performance. These findings aim to inform the strategies that mitigate impacts and align farm management with Taiwan’s sustainability goals.

Methods A cradle-to-orchard-gate life cycle assessment (LCA) was conducted for seven orchards representing conventional, semi-organic, organic, and natural farming systems. Both mass- and area-based functional units (FU_{mass} , FU_{area}) were applied, with the inclusion of major organically certified materials (bio-fertilisers, biocontrol agents, and organically certified pesticides) in life cycle inventories. Primary data on yields, inputs, and cultivation practices (2021–2024) were collected via interviews, while upstream processes were modelled using ecoinvent v3.11 within SimaPro v9.6.01. Impact assessment employed the ReCiPe 2016 midpoint method (*hierarchist* perspective) across 18 impact categories. Hotspot analysis was performed at process and stage levels, and DICs were determined from normalised scores. Agronomic practices were evaluated for their influence on yield and impact rankings, and findings were compared with relevant literature to formulate mitigation recommendations.

Results and discussion Hotspots were mainly associated with fertiliser production and use, packaging material manufacturing, and energy generation. Freshwater eutrophication was the dominant impact in all orchards except N, where human carcinogenic toxicity prevailed. The natural farming orchard consistently showed the lowest impacts due to the absence of fertilisers and pesticides (per kg: $N > C4 > C1 > O > C2 > C3 > S$; per ha: $N > O > C3 > C1 > C4 > S > C2$). Under FU_{area} , the *organic system (OS)* generally outperformed the *conventional system (CS)* ($CS: 1.11E+00 > OS: 1.04E+00$ kg CO₂ eq), whereas under FU_{mass} , OS exhibited higher impacts in 6 categories. Management practices such as reduced fertiliser application, adoption of organically certified materials, winter double-bagging, mechanical weeding, and optimised crop load improved nutrient-use efficiency and yields, demonstrating their contribution to impact mitigation.

Conclusion This first LCA of sugar apple production in Taiwan shows that systems with low fertiliser input and the adoption of organically certified materials, especially natural farming, provide notable environmental benefits. Functional unit choice influences comparative outcomes, while hotspot and DIC analyses identify fertilisers, pesticides, and packaging materials as key targets for mitigation. These findings support Taiwan’s Organic Agriculture Promotion Plan by demonstrating the potential of reduced fertiliser use and organic material adoption. Future research should incorporate life cycle costing and comprehensive agronomic data to evaluate the economic sustainability of organic practices.

Keywords Life cycle assessment (LCA) · Sugar apple · Functional unit (FU) · Organic agriculture · Environmental impact · ReCiPe 2016 · Tropical fruit production

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Abbreviation

FP	Fertiliser production
FeU	Fertiliser use
PP	Pesticide production
PU	Pesticide use
EG	Energy generation
P	Petrol production
D	Diesel production
E	Electricity generation
FBM	Fruit bagging material manufacturing
PaB	Paper bag manufacturing
PIB	Plastic bag manufacturing
MB	Polyester mesh bag manufacturing
PM	Packaging material manufacturing
FNS	Foam netting sleeve manufacturing
CCB	Corrugated cardboard box manufacturing
Se	Seedling production
CP	Cultivation and packaging stage.
BfP	Bio-fertiliser production
BfU	Bio-fertiliser use
PR	Phosphate rock procurement and processing
BAP	Biocontrol agent production
OPC	Organically certified pest control material manufacturing
R	Rice production
Su	Sulphur procurement and processing
SFO	Sunflower oil production
AS	Alkylbenzene sulfonate manufacturing

1 Introduction

Taiwan, often referred to as the “Kingdom of Fruit,” produces a wide variety of tropical and temperate fruits, yielding approximately 2.7 million tonnes and generating revenues of 97.6 billion New Taiwan dollars (≈ 3 billion USD) in 2024 (Agriculture and Food Agency [AFA] 2024). Despite its economic contribution, this success has come at considerable environmental and human health costs, including greenhouse gas emissions, biodiversity loss, soil erosion, pesticide contamination, and freshwater eutrophication. In 2021, Taiwan’s agricultural sector emitted 6.24 million tonnes of CO₂-equivalent greenhouse gas, representing 2.1% of national emissions (Wang and Juang 2023). Agriculture is also responsible for 67% of national N₂O emissions, a potent GHG that poses a major challenge to achieving Taiwan’s net-zero emissions target by 2040 (Wang and Juang 2023). Regionally, decades of fruit cultivation in Li-shan have caused severe soil erosion, biodiversity loss, and eutrophication of rivers and reservoirs (Tseng 2004), while intensive fruit production in Miaoli County has led to soil acidification and the presence of pesticide

residues above regulatory thresholds in harvested fruits due to over-fertilisation and excessive pesticide use (Chang Chien et al. 2024; Lin 2022).

To mitigate these impacts, Taiwan has promoted organic agriculture since 1986. National organic standards for major crops were established in 1996 (Wang 2021), followed by the Agricultural Production and Certification Act (2007), which provided a legal framework for certification, processing, and penalties for fraudulent labelling. The Organic Agriculture Promotion Act, enacted in 2018, further institutionalised support through promotion zones, financial incentives, and clear certification requirements (OAPC n.d.). By 2024, certified organic farmland reached 20,304 ha, with an additional 6708 ha under “eco-friendly” management, representing 3.47% of total farmland (OAPC 2025).

Despite these policies, organic cultivation continues to face challenges, including lower yields, higher production costs, increased labour requirements, and persistent pest and disease pressures (Kumar 2025). To mitigate these limitations, bio-fertilisers—microbial inoculants that colonise the rhizosphere or plant interior—have been promoted for improving soil fertility and suppressing pathogens (Vessey 2003; George et al. 2020). Similarly, biocontrol agents—organisms that reduce pest populations and associated crop damage—have demonstrated efficacy in pest management (Lamine Senghor et al. 2007; Eilenberg et al. 2001; Lei et al. 2023; Biryol et al. 2025). Organically certified pesticides, such as lime–sulphur and sunflower oil emulsions, have also proven effective in citrus and pear systems (Cha et al. 2018; Alves et al. 2022). While such organically certified materials are environmentally benign at the point of application, their upstream production and field use—particularly diesel consumption—may contribute to environmental burdens.

Life Cycle Assessment (LCA) provides a systematic framework for quantifying environmental impacts across the production chain. A complete life cycle typically encompasses raw material extraction, input manufacturing, cultivation, distribution, consumption, and end-of-life stages (Cabot et al. 2022). Consistent with most citrus-related LCA studies, which often exclude post-harvest processes due to data limitations (Cabot et al. 2022; Falcone et al. 2024), this study adopts a “cradle-to-orchard-gate” scope. To capture the diversity of environmental pressures associated with organic fruit production, the ReCiPe 2016 LCIA method was selected due to its comprehensive impact coverage and robust practitioner guidance (Rybaczewska-Błazejowska and Jezierski 2024).

A further challenge in agricultural LCAs concerns the inclusion of agronomic inputs in life cycle inventories (LCIs). Many organic citrus and banana LCAs exclude bio-fertilisers, biocontrol agents, or organically certified pesticides, potentially underestimating environmental burdens

(Martin-Gorriz et al. 2020; Bonales-Revuelta et al. 2022; Wu et al. 2024; Shih and Lu 2025). To address this methodological gap, the present study explicitly incorporates these inputs into the LCI for organic sugar apple (*Annona squamosa*) production.

Sugar apple was selected due to its economic importance, underrepresentation in LCA research, and the diversity of cultivation systems—including conventional, organic, semi-organic, and natural farming. In 2024, Taiwan produced approximately 18,402 tonnes of sugar apple, with Taitung County contributing a majority of national output (Ministry of Agriculture [MOA] 2025a). Even among organically certified orchards, pest and disease management strategies vary substantially, providing a valuable context to examine the environmental implications of different practices (Table 1).

Sugar apple (*Annona squamosa*), a heart-shaped fruit with sweet, custard-like flesh, is native to tropical regions of the Americas and is believed to have been introduced to Taiwan in the seventeenth century. Commercial cultivation remained limited until the 1980s, largely due to its small fruit size and unappealing appearance (Yang 2023). Since then, sugar apple farming has expanded considerably in Taitung, driven by cultivar improvements, rising domestic demand, improved transportation infrastructure, and favourable environmental conditions (Lu PC 2007; Fig. 1). To date, Taitung continues to dominate national production, highlighting the region's suitability for this tropical fruit production and the concentration of modern sugar apple orchards.

This study provides the first comprehensive cradle-to-orchard-gate LCA of sugar apple production in Taitung, explicitly accounting for the upstream environmental burdens of bio-fertilisers, biocontrol agents, and organically certified pesticides. By offering a more complete assessment of organic or eco-friendly fruit production, the findings aim to inform sustainable orchard management practices, guide policy and certification development, and contribute to broader discussions on sustainable tropical fruit production in Taiwan and other subtropical and tropical regions.

2 Methods

2.1 Goal of this study

The goal of this study is to quantify the environmental impacts associated with the life cycle of sugar apple production across different farming systems in Taitung, Taiwan, and to provide information that can support sustainable orchard management and policy development. The results are not intended for public comparative assertions.

2.2 Scope and functional units

Two distinct functional units were applied separately in this study. The mass-based functional unit (FU_{mass}) refers to 1 kg of harvested sugar apple fruit, which serves as the reference flow for this scenario. The area-based functional unit (FU_{area}) refers to 1 hectare of farmland, which is the reference flow for the area-based scenario. Using both units allows assessment of environmental impacts per unit of yield (mass-based) and per unit of land area (area-based), providing complementary perspectives on the sustainability of sugar apple production.

2.3 System boundaries

This study adopted a “cradle-to-orchard-gate” system boundary, meaning that most processes in the sugar apple life cycle, starting from raw material extraction to the point at which the product leaves the orchard gate, were included in the assessment. Under this scope, three stages would ideally be considered: the pre-gate stage, the nursery stage, and the cultivation and packaging stage (Fig. 2).

In Fig. 2, the pre-gate stage includes all processes occurring before materials arrive at the orchard. The nursery stage, spanning the first three years after orchard establishment, comprises land preparation and the cultivation of immature trees. The cultivation stage, beginning in the fourth year, encompasses all field operations associated with the management of mature trees. In this study, the nursery stage was omitted from the system scope, which may lead to an underestimation of the total environmental footprint; however, the extent of this potential underestimation remains uncertain.

2.4 LCA software and impact category (IC)

LCA in this study was conducted using SimaPro PhD v.9.6.01, incorporating the ReCiPe 2016 method at the midpoint level from the *hierarchist* perspective. ReCiPe 2016 includes 18 midpoint *impact categories* (ICs), such as global warming, stratospheric ozone depletion, and ionising radiation, etc (Huijbregts et al. 2017). The analysis generated orchard- and impact-category-specific scores, which were subsequently used to identify environmental hotspots and determine the *DIC*.

2.5 Surveyed orchards

Seven orchards were selected to ensure representativeness in the LCA of sugar apple cultivation, based on farm size and agronomic practices. *Orchard C1* and *C2*, each exceeding three times the national average farmland size of 1.02 ha per household, were classified as large-scale farms

Table 1 Summary of agronomic inputs and management practices among the surveyed orchards

	C1	C2	C3	C4	O	N	S
Fertilisers							
Organic fertiliser	v		v	v	v		v
Synthetic fertiliser	v	v	v	v			v
Bio-fertiliser (PSB)						v	v
Pest control							
Pesticide	v	v	v	v			
Basionym							v
Blower					v		
Fruit bagging							
Paper bag		v		v	v	v	v
Plastic bag (winter)	v		v			v	v
Polyester mesh bag	v						
Disease control							
Fungicide	v	v	v	v			
Lime-sulphur						v	v
Sunflower oil emulsion							v
Weeding							
Herbicide	v	v	v	v			
Backpack lawn mower	v	v	v	v	v (limited)	v	v
Riding mower	v	v	v	v	v (limited)	v	v
Agricultural machinery							
self-propelled sprayer	v	v	v	v		v	v
Backpack sprayer							v
Transport vehicle	v	v	v	v	v	v	v
Irrigation equipment							
Pump	v	v	v	v	v	v	v
Sprinkler	v	v	v	v	v	v	v
Generator		v				v	v
Energy use							
Petrol	v	v	v	v	v	v	v
Diesel	v		v	v		v	v
Electricity	v	v	v	v	v		
Natural environment							
Location	(22.75N, 121.1E)	(22.78N, 121.08E)	(22.76N, 121.06E)	(22.81N, 121.08E)	(22.6N, 121E)	(22.79N, 121.07E)	(22.79N, 121.06E)
Annual temperature ^a	24.7	24.7	24.7	24.7	24.7	24.7	24.7
Annual rainfall ^a	1737.6	1737.6	1737.6	1737.6	1737.6	1737.6	1737.6
Topography ^b	Alluvial fan	Alluvial fan	Alluvial fan	Alluvial fan	Alluvial fan	Alluvial fan	Alluvial fan
Soil type ^b	silty clay loam	silty clay loam	silty clay loam	silty clay loam	silty clay loam	silty clay loam	silty clay loam

^aAnnual temperature and rainfall data for the surveyed orchards were obtained from the Central Weather Administration (Central Weather Administration [CWA] n.d.)

^bTopography and soil type information for the surveyed orchards was obtained from the Ministry of Agriculture (Ministry of Agriculture [MOA] 1984)

(Directorate-General of Budget, Accounting and Statistics [DGBAS] n.d.). Orchards C3 and O, which were close to the national average, were classified as medium-scale, while C4, N, and S, operating at 40–60% of the average, were classified as small-scale (Online Resource 1).

Agronomic inputs—including fertilisers, pest and disease management, fruit bagging, weeding, machinery,

and energy—varied among cultivation systems (Online Resource 1). Organic or eco-friendly orchards (O, N, S) primarily employed blowers and organically certified pest-control materials, such as biocontrol agents or organically certified pesticides, whereas conventional orchards predominantly used synthetic pesticides. These differences are summarised in Table 1.

Fig. 1 Geographic location of Taitung County in Taiwan and its administrative townships. Among the seven surveyed orchards, *orchards C1* and *C3* are located in Taitung City; *orchards C2*, *C4*, *N*, and *S* are situated in Beinan Township; and *orchard O* is located in Taimali Township



Despite variations in size and management practices, all orchards shared similar environmental conditions, being located in low-altitude alluvial plains with silty clay loam (MOA 1984). Although township-scale climate data were not available, temperature and rainfall were assumed to vary minimally due to the limited geographical extent of Taitung County, the orchards' proximity to the Pacific coast, and their low elevations (below 100 m above sea level).

While these seven orchards were selected to capture a range of farm sizes and management practices, we acknowledge that they may not fully represent all sugar apple cultivation systems in Taitung County. Some rare practices or extreme production conditions could be underrepresented. Nonetheless, the selected orchards encompass the major farming strategies—conventional, semi-organic, organic, and natural farming—providing a representative snapshot of current practices and enabling meaningful comparison of environmental impacts across different management systems.

2.6 Data collection

Data for the LCA of sugar apples were collected through direct contact with sugar apple cultivators in Taitung, Taiwan, from October 2024 to November 2025. Seven orchard managers consented to participate and provided data on

annual yield, orchard surface area, and annual quantities of inputs including seedlings, fertilisers, pesticides, fuel, and bagging materials, etc.

Among the seven orchards, four (*C1*, *C2*, *C3*, and *C4*) practiced conventional cultivation methods. The remaining three orchards applied alternative practices: *orchard O* employed *organic farming*, *orchard N* followed *natural farming*, and *orchard S* adopted a *semi-organic* (or eco-friendly) *approach*. These distinct cultivation methods resulted in variation in both types and quantities of material and energy inputs (Online Resource 1). Accordingly, each orchard was treated as an individual production system; hence, the terms “orchard” and “production system” were used interchangeably throughout this study.

Inventory data were modelled using ecoinvent v.3.11 datasets within Simapro. The Recipe 2016 methodology was then applied to calculate characterised and normalised impact scores.

2.7 Life cycle inventory analysis

2.7.1 Data used for this study

The Life Cycle Inventory (LCI) framework for this study was established based on standard agronomic practices associated with sugar apple cultivation (Fig. 3). Primary

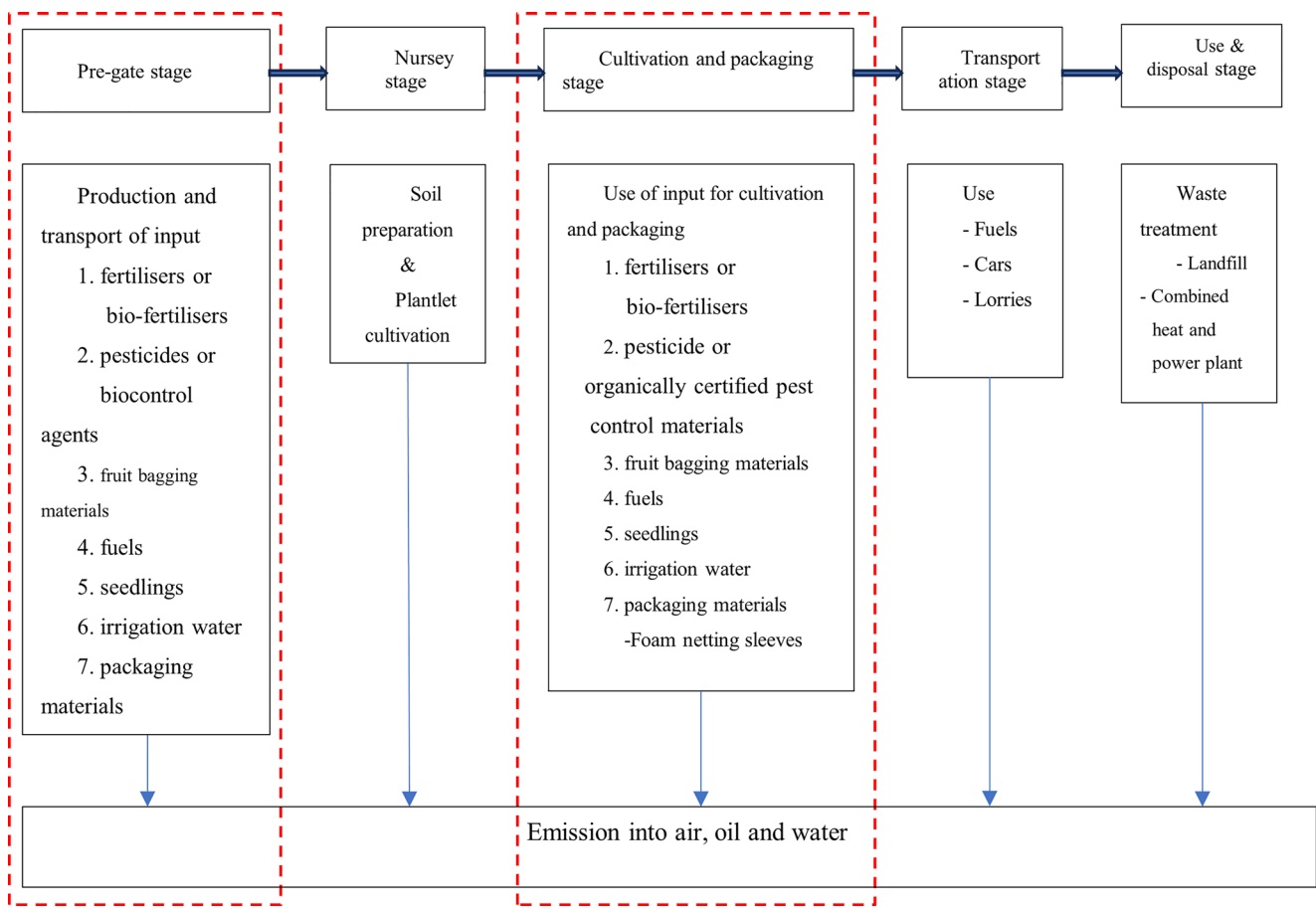


Fig. 2 Life cycle of sugar apples and the system boundaries of this study (indicated by dashed red lines)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Summer production cycle	Pruning														
			Flowering → Artificial pollination → Fruit thinning → Fruit bagging												
								Harvest season							
Winter production cycle						Pruning									
							Flowering → Artificial pollination → Fruit thinning → Fruit bagging								
										Harvest season					

Fig. 3 Time span and sequence of main agricultural practices during the cultivation stage of sugar apple in the summer production cycle (yellow cells) and the winter production cycle (green cells)

data were obtained through structured interviews with managers from seven orchards located in Taitung, Taiwan. On an annual average basis, the inventory encompasses the following parameters: orchard area; annual yields (2021–2024); quantities of seedlings; types and application rates of fertilisers or bio-fertilisers (e.g., photosynthetic bacteria); types and dosages of pesticides (e.g., synthetic herbicides,

insecticides, and fungicides), biocontrol agents (basionym), and organically certified pesticide (sunflower oil emulsion, and lime-sulphur); quantities of bagging materials used (e.g., paper bags, plastic bags, polyester mesh bags); types and quantities of packaging materials used (e.g., foam netting sleeves, corrugated cardboard boxes); and energy inputs, including diesel fuel, gasoline, and electricity (Online

Resource 1; Fig. 2). Irrigation water use was excluded from the system boundary due to insufficient quantitative data, as reported by orchard managers.

The aforementioned information, provided by orchard managers, was entered into the SimaPro v9.6.01 software using the corresponding built-in modules. When multiple modules were available for a specific input, priority was given to the one most compatible with the input in terms of geographical coverage and material characteristics.

2.7.2 Estimation of N_2O , NO , CH_4 , and NH_3 emission

At the cultivation stage of the sugar apple life cycle, the application of nitrogen fertilisers—whether organic or synthetic—inevitably results in emissions of gases such as N_2O , NO , CH_4 , and NH_3 . N_2O and NO are greenhouse gases that contribute to *global warming*, whereas NH_3 is associated with *terrestrial acidification* and both *freshwater and marine eutrophication* (Huijbregts et al. 2017). In this study, priority was given to emission factors from local orchard studies that differentiated between organic and synthetic fertiliser inputs. When such local emission factors were unavailable, data from other local upland crop studies were used; in the absence of local data, global statistics were applied. For N_2O emissions, the emission factor was set at 1.63% of the total nitrogen input (Chien et al. 2010). For NO emissions, the emission factor were 0.4% for organic fertilisers and 0.6% for synthetic fertilisers (Food and Agriculture Organization [FAO] 2001). For CH_4 emission to air, the rate was set at 0.433 kg ha^{-1} (Yang et al. 2003). For NH_3 emissions to air, the rates were 15.66% and 11.76% of the total nitrogen input for organic and synthetic fertilisers, respectively (Hsu et al. 2023).

2.7.3 Estimation of synthetic pesticide emission

The environmental and human health impacts of on-field synthetic herbicide, fungicide, and insecticide emissions (collectively referred to as synthetic pesticides) were assessed following the methodology of the *World Food LCA Database* (WFLD). In this approach, it is assumed that 100% of the active substance applied to the field is emitted to agricultural soil, representing the fraction of pesticide that directly interacts with the soil environment (Bengoa et al. 2019). Within SimaPro, the default ecoinvent characterisation factors at the global scale were applied to convert these soil emissions into midpoint impact category scores, thereby enabling quantification of the potential environmental and human health burdens associated with pesticide use.

2.7.4 Allocation procedure

This study applied the cut-off allocation approach, consistent with the “Allocation, cut-off by classification” system model of the Ecoinvent 3.11 database used in SimaPro. In this approach, all environmental burdens are assigned to the primary product, while recyclable or reusable materials are treated as burden-free at the point they enter the system. Likewise, recyclable outputs are excluded from the system boundaries without credit. This method aligns with the goal of evaluating the environmental impacts directly associated with sugar apple production at the orchard level.

2.8 Uncertainty analysis

The main sources of uncertainty in LCAs arise from input uncertainty, data variability, and the cumulative effects of model imprecision due to the complexity of representing environmental interactions (ISO 2006). In this study, the LCA software used (SimaPro PhD v.9.6.01) accounts for input data dispersion by assigning standard deviations to all input data and parameters. A Monte Carlo simulation—with default lognormal distributions and 1000 iterations—was applied to propagate uncertainty and assess the robustness of the LCA outputs. This simulation generated the spread of results (95% confidence intervals) for each impact category across all orchards.

2.9 Sensitivity analysis

A one-factor-at-a-time (OAT) sensitivity analysis was conducted to evaluate the influence of key parameters on the robustness of hotspot identification across the seven orchards. For orchards that applied fertiliser (*C1–C4*, *O* and *S*), two parameters related to fertiliser use were tested: the fertiliser application rate and the N_2O emission factor, each varied by $\pm 20\%$ from their baseline values. For *orchard N*, which did not apply fertiliser, *packaging material manufacturing* was the principal contributor to impacts; therefore, the quantity of packaging materials (and associated manufacturing processes) was similarly varied by $\pm 20\%$. Sensitivity was quantified using the Sensitivity Index (SI), calculated as the ratio of the relative change in the impact result to the relative change in the input parameter. This procedure provides a consistent basis for comparing parameter influence across orchards with differing production characteristics.

3 Results

This section presents the environmental impact assessment of seven sugar apple orchards using two distinct functional units. It first reports characterised impact scores across multiple categories, followed by a comparative ranking of orchard performance. Hotspot analyses then identify the key contributing processes and life cycle stages, while normalised scores highlight the dominant impact categories (DIC) for each orchard and across all surveyed orchards. Comparisons between conventional and organic systems are subsequently made to illustrate differences in environmental burdens and potential trade-offs. Finally, the environmental footprint of sugar apple is compared with that of other tropical fruits.

3.1 Characterised impact scores

The characterised impact scores for each impact category varied depending on the functional units applied. Online Resource 3 presents the characterised scores of the seven orchards under the FU_{mass} and FU_{area} , respectively. These scores reveal noticeable variations between orchards within each impact category, largely reflecting differences in farming practices and input intensities.

3.2 Overall comparative rankings of orchards

To determine the overall ranking of each orchard, a systematic ranking procedure was applied based on the characterised impact scores. First, each orchard was ranked within each *impact category* based on its characterised scores, where the orchard with the lowest score (best performance) received rank 1, and the orchard with the highest score (worst performance) received rank 7. Second, an average rank for each orchard was calculated by averaging its *impact category*-specific ranks. Third, the orchards were re-ranked according to their average ranks to obtain an overall comparative ranking. Rankings were conducted separately for the two functional units.

When the FU_{mass} was applied, the ranking from best to worst was *N*, *C4*, *C1*, *O*, *C2*, *C3*, *S* (Table 2). Under the FU_{area} , the ranking order was *N*, *O*, *C3*, *C1*, *C4*, *S*, *C2* (Table 2). In both cases, *orchard N* (natural farming system) consistently emerged as the top performer, which can be attributed to its complete avoidance of both fertilisers and synthetic pesticides (Online Resource 1). This absence of input-intensive practices, along with the adoption of bio-fertilisers and biocontrol agents resulted in significantly lower environmental impacts across multiple categories, highlighting the environmental advantage of low-input systems.

3.3 Hotspot analysis

Hotspot analysis was conducted for each orchard at the *process* and *stage* levels respectively, based on their orchard- and impact category-specific characterised scores. At the process level (or stage level), *dominant hotspots* were identified by sequentially including the *impact-category-level hotspots* with the highest frequency of occurrence until they accounted for more than 50% of the total impact categories. Using this criterion, *fertiliser use*, *fertiliser production*, *packaging material manufacturing* (PM), and *energy generation* emerged as *dominant hotspots*, as they contributed most significantly to multiple *impact categories* within each orchard (Table 3).

Specifically, *fertiliser use* was the *dominant hotspot* in all orchards except *orchard C4* and *N*. In *orchard C4*, had the 50% impact category coverage criteria been lifted, *fertiliser use* would have been the second order dominant hotspot. In *orchard N*, no fertilisers application was the reason why *fertiliser use* wasn't its dominant hotspot. Fertiliser production was identified as a dominant hotspot in *orchards C2*, *C3*, *C4*, and *S*, likely due to heavy metal emissions from phosphate rock, depletion of phosphate and potash deposits, the energy-intensive Haber–Bosch process, and process water use. This was reflected in the shared impact category-level hotspots of *terrestrial ecotoxicity* (TE), *mineral resources scarcity* (MRS), *fossil resource scarcity* (FRS), and *water use* (WU) (Table 2; Online Resources 5, 6, 7, and 10).

Packaging material manufacturing was the dominant hotspot in *orchard C3*, *O* and *N*, driven primarily by the upstream *corrugated cardboard box manufacturing* (CCB) (Online Resource 6, 8 & 9). *Energy generation* was the *dominant hotspot* in *orchard C1* and *N*, driven mainly by the upstream *petroleum manufacturing* (Online Resource 4 & 9).

The identification of *fertiliser use* as a key hotspot aligns with the results of Bessou et al. (2016), Nicolò et al. (2017), Pergola et al. (2013), and Yang et al. (2020), who also highlighted *fertiliser use* as a dominant contributor in citrus life cycles. Likewise, the identification of *fertiliser production* as a dominant hotspot in the sugar apple life cycle is consistent with the findings of Alishah et al. (2019) and Ribal et al. (2017), both of whom identified *fertiliser production* as a major hotspot in citrus life cycles.

At the stage level, the *pre-gate stage* was identified as the dominant hotspot across all orchards (Table 2), suggesting the importance of carefully selecting input such as fertilisers, energy sources, and packaging materials to mitigate environmental impacts.

Table 2 Orchard-level rankings across midpoint impact categories under mass-based and area-based functional units (FUs). For each of the midpoint ICs, orchards are ranked from 1 (lowest characterised result) to 7 (highest), separately under the mass-based FU (left section) and area-based FU (right section). The final two rows present the average rank across all impact categories and the resulting overall ranking of each orchard under each FU

IC	Mass-based FU							Area-based FU						
	C1	C2	C3	C4	O	N	S	C1	C2	C3	C4	O	N	S
GW ^a	3	5	4	2	6	1	7	5	7	2	4	3	1	6
SOD ^b	3	4	5	2	7	1	6	4	7	3	2	5	1	6
IR ^c	5	3	6	2	4	1	7	5	7	4	3	2	1	6
OFH ^d	3	5	4	2	6	1	7	5	7	2	4	3	1	6
FPM ^e	4	3	5	2	7	1	6	4	7	3	2	6	1	5
OFT ^f	3	5	4	2	6	1	7	5	7	2	4	3	1	6
TA ^g	4	3	5	2	7	1	6	4	7	3	2	6	1	5
FeU ^h	3	4	5	2	6	1	7	5	7	4	2	3	1	6
MEu ⁱ	3	6	5	4	1	2	7	5	7	3	6	1	2	4
TE ^j	3	4	2	5	6	1	7	4	7	2	6	3	1	5
FEc ^k	7	4	6	5	2	1	3	5	7	4	6	1	2	3
MEc ^l	6	4	3	7	2	1	5	5	6	3	7	1	2	4
HCT ^m	2	5	6	3	4	1	7	4	7	3	5	2	1	6
HNC ⁿ	5	2	6	4	3	1	7	5	7	3	6	1	2	4
LU ^o	1	4	2	3	6	5	7	3	7	1	6	2	4	5
MRS ^p	3	7	4	5	1	2	6	3	7	4	6	1	2	5
FRS ^q	4	6	5	3	1	2	7	4	7	3	5	1	2	6
WC ^r	3	7	5	4	1	2	6	3	7	4	6	1	2	5
Average rank	3.61	4.5	4.56	3.28	4.22	1.44	6.39	4.33	6.94	2.94	4.56	2.5	1.56	5.17
Overall ranking	3	5	6	2	4	1	7	4	7	3	5	2	1	6

^aGW = Global warming. ^bSOD = Stratospheric ozone depletion. ^cJR = Ionizing radiation. ^dOFH = Ozone formation. ^eFPM = Fine particulate matter formation. ^fOFT = Ozone formation. ^gTA = Terrestrial acidification. ^hFeU = Freshwater eutrophication. ⁱMEu = Marine eutrophication. ^jTE = Terrestrial ecotoxicity. ^kFEc = Freshwater ecotoxicity. ^lMEc = Marine ecotoxicity. ^mHCT = Human carcinogenic toxicity. ⁿHNC = Human carcinogenic toxicity. ^oLU = Land use. ^pMRS = Mineral resource scarcity. ^qFRS = Fossil resource scarcity. ^rWC = Water consumption

Table 3 Impact category (IC), process, and stage level hotspots across orchards. The final second and third rows indicate the first-order and, where applicable, second-order dominant hotspots (DH) for each orchard, based on the frequency of dominant process appearances across all impact categories

	C1	C2	C3	C4	O	N	S
<i>IC level hotspot</i>							
GW	FeU	FP	FeU	FP	FeU	EG	FeU
SOD	FeU	FeU	FeU	FeU	FeU	PM	FeU
IR	PP	FP	PP	FP	EG	PM	FP
OFH	EG	FeU	FeU	FeU	FeU	EG	FeU
FPM	FeU	FeU	FeU	FeU	FeU	EG	FeU
OFT	EG	FeU	FeU	FeU	FeU	EG	FeU
TA	FeU	FeU	FeU	FeU	FeU	EG	FeU
FeU	FeU	FeU	FeU	FeU	FeU	PM	FeU
MEu	PM	PM	PM	PM	PM	PM	PM
TE	EG	FP	FP	FP	FP	EG	FP
FEc	PU	PU	PU	FP	PM	PM	FP
MEc	PU	PM	PM	FP	PM	PM	FP
HCT	PM	FP	PM	FP	EG	PM	FP
HNC	EG	FP	PU	FP	EG	EG	FP
LU	PM	PM	PM	PM	FBM	FBM	PM
MRS	FP	FP	FP	FP	PM	PM	FP
FRS	EG	FP	FP	FP	EG	EG	FP
WC	PM	FP	FP	FP	PM	PM	FP
<i>Process level hotspot</i>							
1st order DH	FeU, EG	FP	FeU	FP	FeU	PM	FP
2nd order DH		FeU	FP, PM		PM	EG	FeU
<i>Stage level hotspot</i>							
	Pregate	Pregate	Pregate	Pregate	Pregate	Pregate	Pregate

3.4 Normalised scores and dominant impact categories (DIC)

Normalised scores enable cross-category comparisons of environmental impacts, thereby facilitating the identification of the DIC, defined as the impact category with the highest normalised score at the orchard level or across orchards. At the orchard level, under either FU_{mass} or FU_{area} , the DIC was *freshwater eutrophication (FeU)* in each orchard except for *N*, mainly due to their on-field *fertiliser use* (Online Resource 3, 4, 5, 6, 7, 8 & 10; Fig. 4). In orchard *N*, *human carcinogenic toxicity (HCT)* was its DIC mainly due to its upstream *packaging material manufacturing* (Online Resource 9; Fig. 4).

At the cross-orchard level, under FU_{mass} , the top three normalised scores were observed in orchards *S*, *O*, and *C3* in descending order, all within the category of *freshwater eutrophication (FeU)* (Online Resource 11; Fig. 4a). Within this category, the primary hotspot in each of these orchards was linked to their *fertiliser use (FeU)* (Table 3). Under FU_{area} , the top three normalised scores were observed in orchards *C2*, *S*, and *C1* in descending order, all within the category of *freshwater eutrophication (FeU)* (Online Resource 11; Fig. 4b). Within this category, the primary hotspot in each of these orchards was also linked to their *fertiliser use (FeU)* (Table 3).

Collectively, these findings suggest that reducing or substituting the use of fertilisers should be prioritised as key strategies for environmental impact mitigation.

3.5 Conventional vs. Organic system categories

The orchards were classified as either the *conventional system category (CS)* or the *organic system category (OS)* based on their certification status. Among the seven orchards, CS included *C1*, *C2*, *C3*, *C4*, and *S*, while OS comprised orchards *O* and *N*. Comparisons between CS and OS were conducted category by category using weighted characterised scores, with yield and area serving as weighting factors under the FU_{mass} and FU_{area} , respectively. Under the FU_{mass} , CS exhibited higher impacts than OS within all categories, except for *stratospheric ozone depletion (SOD)*, *fine particulate matter formation (FPM)*, *ozone formation human health* and *terrestrial ecosystem (OFH, OFT)*, *terrestrial acidification (TA)*, and *land use (LU)*, where OS showed slightly higher values (Table 4). Under the FU_{area} , CS consistently presented higher impacts across all midpoint categories (Table 4).

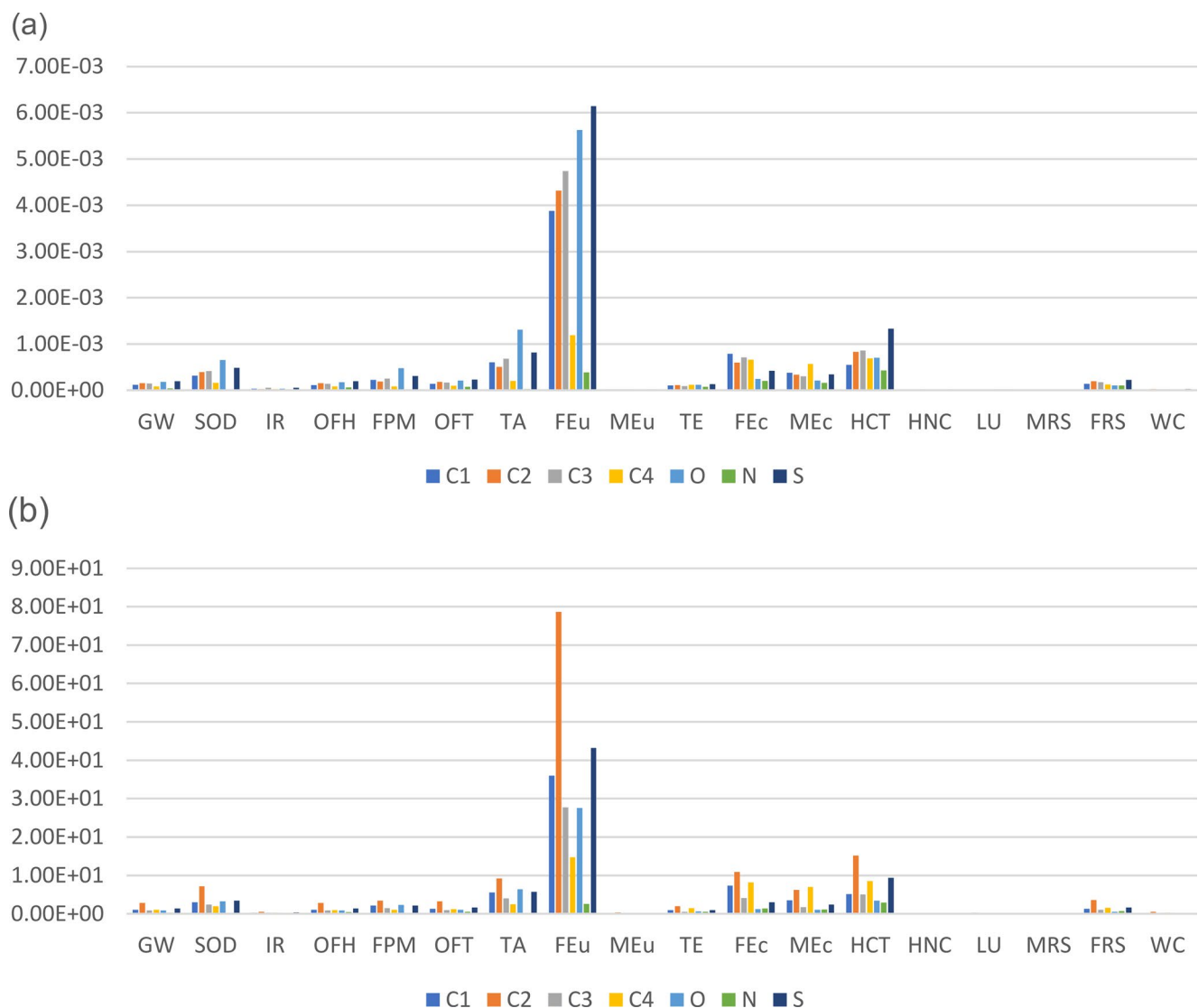


Fig. 4 Normalised scores of each impact category for individual orchards under (a) mass-based and (b) area-based functional units. The bars represent the relative magnitude of environmental impacts

across orchards and impact categories after normalisation, facilitating comparison of impact significance both within and between orchards

3.6 Uncertainty evaluation

Uncertainty indicators from the Monte Carlo simulations are summarised in Online Resource 12. Most impact categories showed low to moderate uncertainty (CV 0.07–71.72), whereas toxicity-related categories, as well as ionising radiation, exhibited considerably higher variability (CV up to 236.2). The elevated uncertainty in these categories reflects the large variability in toxicity characterisation factors, limited availability of chemical-specific emission data, the sensitivity of toxicity models to assumptions on pesticide fate and transport, and the dominance of background processes. Water consumption showed extremely high uncertainty (CV up to 1821.08) because no irrigation inputs were reported. Across orchards, several categories displayed overlapping

95% confidence intervals, while others remained clearly separated, indicating that the robustness of inter-orchard comparisons is category-dependent but largely preserved for most impact categories.

3.7 Sensitivity analysis

Across the fertiliser-using orchards (C1–C4, O and S), the sensitivity index (SI) for the $\pm 20\%$ fertiliser application scenarios ranged from 0.01 to 0.99, reflecting very low to moderate sensitivity depending on the impact category. The SI for the $\pm 20\%$ variation in the N_2O emission factor ranged from 1.01 to 1.67, indicating high sensitivity. For orchard N, which did not apply fertiliser, the SI associated with the $\pm 20\%$ variation in packaging materials manufacturing

Table 4 Comparison of normalised impact scores between the *conventional system category* (CS) and the *organic system category* (OS) across 18 impact categories under mass-based and area-based functional units (FU). These figures highlight the system-level environmental performance differences under each FU, providing insights into the relative sustainability of conventional and organic sugar apple production

	Mass-based FU			Area-based FU		
	CS	OS	CS-OS	CS	OS	CS-OS
GW	1.39E-04	1.30E-04	9.02E-06	1.72E+00	9.37E-01	7.82E-01
SOD	3.61E-04	4.30E-04	-6.87E-05	4.47E+00	2.07E+00	2.40E+00
IR	3.09E-05	2.55E-05	5.46E-06	3.83E-01	2.74E-01	1.09E-01
OFH	1.38E-04	1.38E-04	-2.66E-07	1.70E+00	1.01E+00	6.98E-01
FPM	2.00E-04	3.17E-04	-1.17E-04	2.48E+00	1.36E+00	1.12E+00
OFT	1.62E-04	1.63E-04	-7.01E-07	2.01E+00	1.19E+00	8.18E-01
TA	5.35E-04	8.62E-04	-3.28E-04	6.62E+00	3.52E+00	3.11E+00
FeU	4.08E-03	3.80E-03	2.83E-04	5.06E+01	2.69E+01	2.36E+01
MEu	1.74E-05	1.30E-05	4.42E-06	2.16E-01	1.19E-01	9.74E-02
TE	1.07E-04	1.04E-04	2.50E-06	1.32E+00	7.78E-01	5.46E-01
FEc	6.58E-04	2.31E-04	4.27E-04	8.15E+00	2.33E+00	5.82E+00
MEc	3.63E-04	1.91E-04	1.71E-04	4.49E+00	1.89E+00	2.60E+00
HCT	7.57E-04	6.07E-04	1.50E-04	9.38E+00	6.79E+00	2.58E+00
HNC	1.21E-05	9.96E-06	2.11E-06	1.49E-01	9.85E-02	5.10E-02
LU	1.32E-05	1.66E-05	-3.39E-06	1.63E-01	1.15E-01	4.88E-02
MRS	2.85E-08	1.02E-09	2.75E-08	3.53E-04	1.27E-04	2.26E-04
FRS	1.74E-04	1.04E-04	6.99E-05	2.15E+00	1.24E+00	9.13E-01
WC	2.18E-05	7.82E-06	1.40E-05	2.70E-01	1.34E-01	1.37E-01

ranged from 0.23 to 0.87, indicating low to moderate sensitivity. Although the specific parameters differed between orchards, the overall pattern remained consistent: each orchard's principal hotspot in the baseline scenario continued to dominate under perturbed conditions, confirming the robustness of the hotspot identification.

4 Discussion

This section examines how agricultural practices affect sugar apple yield and environmental performance and compares its environmental footprints with other tropical fruits, highlighting key hotspots and policy implications.

4.1 Conventional vs. organic farming

Whether conventional or organic farming exerts greater environmental and human health impacts remains a topic of ongoing debate in LCA studies. A major reason for the divergent findings lies in the choice of functional units. For example, Ribal et al. (2017) assessed orange production using both mass- and area-based functional units across seven midpoint categories and found that conventional systems generally had higher impacts under an FU_{area} . In contrast, when a FU_{mass} was applied, organic systems showed higher impacts in two categories: *acidification potential* and *eutrophication potential*. Similarly, a meta-analysis by Tuomisto et al. (2012) found that organic farming in Europe typically performed better than conventional farming under

an FU_{area} , while the comparative advantage diminished or reversed under a FU_{mass} .

Our results align with these earlier studies, demonstrating that the relative environmental performance of organic and conventional systems is highly sensitive to the choice of functional units. As in Ribal et al. (2017) and Tuomisto et al. (2012), the *organic system category* (OS) in our study consistently showed lower environmental impacts than the *conventional system category* (CS) when impacts were expressed per unit area. However, this advantage was less consistent under the FU_{mass} (Table 4). Notably, OS showed slightly higher impacts in 6 categories likely due to fertiliser use, upstream paper related material inputs (paper bags and corrugated cardboard boxes), and energy generation (petrol) (Table 4; Online Resources 8 & 9). These exceptions illustrate how specific practices in organic systems can offset some of their environmental advantages and underline the importance of hotspot-level analysis when interpreting LCA outcomes.

For agricultural decision-making, the selection of materials and their use efficiency within OS (e.g., types of energy sources, organic fertilisers, fruit bagging, and packaging materials) should be carefully managed to avoid burden-shifting across impact categories. From a methodological perspective, the observed sensitivity to functional unit choice reinforces the importance of multi-FU reporting in LCA studies to ensure robust and policy-relevant conclusions. In addition, labour hours per unit area in organic and semi-organic systems (3387.74–3763.22 hr/ha) were generally higher than in their conventional counterparts

(1690.86–2634.26 hr/ha), indicating substantially greater labour requirements for organic and semi-organic systems per unit area (Online Resource 1). Given the current labour shortage and ageing farming population in Taiwan, higher labour demands may pose additional operational challenges for organic and semi-organic producers, highlighting the need for supportive measures to ensure adequate labour availability within the agricultural sector.

4.2 Nutrient input

By comparing the Ministry of Agriculture (MOA) recommended fertiliser application rates with actual on-field application data (Ministry of Agriculture [MOA] n.d.), we found that on-field total nitrogen input as a percentage of the official recommendation, ranged from 0% to 130.58%; P_2O_5 input from 3% to 230.29%; and K_2O input from 3% to 121.92% (Table 5). These results indicate substantial variability in nutrient input levels among the surveyed orchards. Moreover, yields were broadly comparable across the surveyed orchards, supporting the use of nutrient input per unit yield as a proxy for nutrient use efficiency in this study.

Among the surveyed orchards, *orchard N* exhibited the lowest nutrient input per unit yield—used here as an indicator of nutrient use efficiency—reflecting the absence of both organic and synthetic fertiliser application and reliance on bio-fertiliser practices (Online Resource 1). Excluding the

natural farming system (*orchard N*), *orchard C4* achieved the lowest nutrient input per unit yield among the remaining orchards (22.39, 12.82, and 41.02 kg ton⁻¹ for total nitrogen, P_2O_5 , and K_2O , respectively), indicating the highest nutrient use efficiency under mixed organic–synthetic fertilisation conditions, in the absence of bio-fertiliser application (Online Resource 1). These results suggest that, in the absence of bio-fertiliser application, current official fertiliser recommendations may exceed the nutrient inputs typically required to sustain high productivity.

As at least 70% of the trees in each surveyed orchard were older than seven years, major differences in nutrient demand are unlikely, although soil fertility and pruning practices may also influence nutrient requirements (Wang et al. 2022; Carranca et al. 2018). Under production systems without bio-fertiliser use, fertiliser application rates comparable to those observed in *orchard C4* may therefore serve as a reference for improving nutrient use efficiency while maintaining relatively high yields (Online Resource 1). Such reductions in fertiliser inputs would be expected to lower emissions of N_2O and ammonia, as well as nitrate and phosphorus leaching, thereby contributing to reduced impacts on global warming potential and freshwater eutrophication (Huijbregts et al. 2017).

Table 5 Inventory data and associated statistics of the surveyed sugar apple orchards in Taitung, Taiwan. Full table is available in Online Resource 1

	Unit/Definition	C1	C2	C3	C4	O	N	S
Orchard size	ha	3.88	3.69	0.97	0.58	1	0.39	0.58
Average yield	kg/yr	36000	67189	5673	7182	4895	2619	4093
Average yield	ton/yr	36	67.19	5.67	7.18	4.9	2.62	4.09
Average yield per unit area	kg/ha/yr	9279	18230	5849	12341	4895	6751	7033
Harvest Season	s = summer. w = winter	s,w	s,w	w	s,w	s,w	s,w	s,w
Crop load	N of fruits/tree/year	50	70	30	40	40	40	40
Crop load per harvest season	N of fruits/tree/year	25	35	30	20	20	20	20
Nutrient input	kg/ha/yr							
Total Nitrogen input		590	1144	446	276	679	0	628
P_2O_5 input		499	1068	384	158	385	12 ^a	583 ^b
K_2O input		605	1068	442	506	665	20 ^a	585 ^b
Recommended input	kg/ha/yr							
Total Nitrogen input		876	876	789	876	680	767	657
P_2O_5 input		464	464	418	464	360	406	348
K_2O input		876	876	789	876	680	767	657
On-field/Recommended ratio	%							
Total Nitrogen input		67.36%	130.58%	56.57%	31.53%	99.85%	0%	95.59%
P_2O_5 input		107.65%	230.29%	91.85%	34.11%	106.94%	3%	167.53%
K_2O input		69%	121.92%	55.98%	57.76%	97.79%	3%	89.06%

^aDespite the absence of direct fertiliser application in *orchard N*, nutrient inputs are accounted for in the life cycle inventory due to upstream inputs associated with phosphate rock (PR) and potassium ore (K_2SO_4) used as raw materials in the production of photosynthetic bacteria liquid (bio-fertiliser)

^bIn *orchard S*, nutrient inputs in the life cycle inventory include both direct fertiliser inputs and upstream inputs associated with phosphate rock (PR) and potassium ore (K_2SO_4) used as raw materials in the production of photosynthetic bacteria liquid (bio-fertiliser)

4.3 Organic vs. synthetic fertilisers

Previous studies have shown that the production and use of synthetic fertilisers generally result in greater environmental impacts than those of organic fertilisers. In terms of production, synthetic fertilisers typically have higher energy demands and contribute more significantly to non-biogenic greenhouse gas (GHG) emissions (Lehigh University 2018). Although composting organic waste also generates GHG emissions, the environmental performance of organic fertiliser production can be further improved through technologies such as anaerobic digestion and solid–liquid separation, which can reduce GHG emissions from raw slurry processing by up to 71%. Consequently, GHG emissions from the production of organic fertilisers (excluding biogenic CO₂) can be comparable to those of synthetic nitrogen fertilisers (EU CAP Network n.d.; Walling and Vaneeckhaute 2020).

Regarding use, organic fertilisers—such as compost, manure, and cover crops—release nutrients more gradually, improve soil structure, enhance microbial activity, and support long-term soil health (Diacono and Montemurro 2010). While the organic fertilisers can emit GHGs after application, their field-level emissions are generally lower than those of synthetic fertilisers in upland cropping systems with minimal irrigation (Fan et al. 2023). Taken together, these findings suggest that organic fertilisers represent a more environmentally sustainable option, particularly when advanced manure treatment technologies are employed.

4.4 Bio-fertilisers and organically certified pest control materials

Bio-fertilisers and organically certified pest control materials—including biocontrol agents and organically certified pesticides—were applied in *orchards N* and *S*, though the specific inputs differed. Both orchards used photosynthetic bacteria (as bio-fertiliser) and lime–sulphur (as organically certified pesticide), while sunflower oil emulsion (as organically certified pesticide) and basionym (as biocontrol agent) were applied exclusively in *orchard S*.

Application rates of both bio-fertilisers and organically certified pest control materials in *orchard N* were approximately 3–15 times higher per hectare than those in *orchard S* (Online Resource 1), yet yields per hectare were comparable (Table 5; Online Resource 1). However, since overall agronomic management practices—especially fertiliser regimes—also differed, it cannot be determined whether the higher application rates in *orchard N* reflect inefficient or unnecessary. Further research is therefore needed to identify optimal application rates that balance yield performance with environmental impact mitigation under different management scenarios.

From an environmental and human health perspective, bio-fertiliser production (*BfP*) and use (*BfU*) contributed minimally to most impact categories in both orchards (Online Resources 9&10). An exception was bio-fertiliser use (*BfU*) in *orchard N*, which accounted for 30.6% of the total freshwater eutrophication impact score, although this contribution remained secondary to packaging material manufacturing (PM; 34.66%) (Online Resources 9). This higher contribution reflects the substantially greater bio-fertiliser application rate in *orchard N*, roughly three times that of *orchard S* (Online Resource 1).

Similarly, organically certified pest control materials contributed only marginally to total impacts (<4.61%) across all midpoint categories (Online Resources 9 and 10), indicating negligible environmental burdens under the application rates observed in this study. These findings suggest that broader adoption of bio-fertilisers and organically certified pest control materials may not substantially increase impacts, despite one category-specific exception observed under higher application rates. Future work could assess whether such inputs might offer yield-supporting options in low-input systems such as *orchard O*, which applied no pesticides and exhibited the lowest yield per hectare.

Foerster et al. (2024) reported a substantially higher contribution of lime–sulphur application (24.7%) to the midpoint aggregated single score in organic systems. While not directly comparable with the category-specific midpoint characterisation approach applied in the present study, the higher contribution observed by Foerster et al. (2024) can be attributed to lime–sulphur application rates exceeding those in *orchard N* by more than threefold, thereby increasing upstream burdens associated with pesticide production (Online Resource 1; Foerster et al. 2024).

4.5 Organic production systems: natural farming and organic farming

In this study, *orchards N* and *O* fall into the *organic system category (OS)*. Natural farming, as adopted by *orchard N*, avoids ploughing, fertilization, pesticide use, and even activities such as composting or weeding, following the philosophy of Fukuoka (1978), who believed that undisturbed natural processes could sustain soil vitality and ecological balance. Except for its no-weeding policy, and its adoption of bio-fertilisers (photosynthetic bacteria) and biocontrol agents (lime-sulphur), *orchard N* generally followed the principles of natural farming, resulting in the best overall environmental performance rankings (Table 2).

In contrast, organic farming—practiced at *orchard O*—utilises naturally derived substances (e.g., organic fertilisers) to provide nutrients and employs mechanical tools (e.g., blowers) for pest control. Unlike natural farming, organic

practices allow certain low-impact technologies and interventions and are typically subject to certification standards (Reganold and Wachter 2016).

In this study, the consistently superior performance of *orchard N* (natural farming system), as evidenced by its best environmental performance, highlights the substantial environmental benefits of avoiding both organic fertilisers and pesticides, while relying on bio-fertilisers, biocontrol agents, and organically certified pesticides. Given that the adoption of bio-fertilisers and biocontrol agents accounted for a small proportion of environmental impacts across all categories, these results suggest that the natural farming system of *orchard N* could serve as a benchmark for sustainable orchard management, particularly due to its low-input and low-impact characteristics (Online Resource 9).

Furthermore, *organic farming (orchard O)* demonstrated relatively favourable rankings (second and fourth under different functional units), indicating its potential as a more environmentally sustainable alternative to conventional practices (Table 2). These findings highlight the need for policy support and incentives to encourage the adoption of natural and organic farming practices, including subsidies, technical guidance, and knowledge transfer programmes aimed at reducing the environmental footprint of fruit production.

4.6 Orchard floor management: clean cultivation vs. grass cultivation

Clean cultivation and grass cultivation are two types of floor management practices, each of which was implemented in the orchards surveyed in this study. Clean cultivation refers to the practice of keeping the soil surface free from weeds, plant residues, and other organic matter through regular tillage or mechanical techniques (National Agricultural Law Center n.d.; Merwin et al. 1994, 1999). This method is intended to reduce weed competition, manage pests, and enhance soil aeration (Chauhan et al. 2012; Oerke EC 2006; Khan 1996). In contrast, grass cultivation involves the intentional establishment and maintenance of grasses, primarily to prevent soil erosion, improve soil structure, and promote biodiversity (Conant et al. 2001; Simon et al. 2011).

In this study, clean cultivation was practiced in all production systems except for *orchard O*, where grass cultivation was adopted. While both conventional and organic systems may implement clean cultivation, the weeding methods varied. In conventional systems, weeding was primarily conducted through the use of herbicide, and the backpack or riding mowers. In contrast, in the semi-organic and organic production system of *orchard O*, *N*, and *S*, weeding was performed using only backpack or riding

mowers, in compliance with the policy prohibiting pesticide use, including herbicides (Table 1).

Although the absence of herbicide application in *orchards O*, *N*, and *S* reduced their herbicide-related impact scores to zero, the increased labour hours required for weeding—together with the higher market prices of organic sugar apples—highlight the need for a *life cycle costing* (LCC) study to evaluate the economic efficiency and sustainability of using backpack mowers (especially for weeding under fruit trees) for weed management.

Regarding the impact of floor management on yields, studies by Suo et al. (2019) and Tu et al. (2021) suggested that maintaining natural grass cover may result in lower fruit yields compared to clean cultivation, due to competition for water and nutrients. In this study, these findings were supported by the lowest yield per unit area observed in *orchard O*, where natural grass was maintained (Table 5). Given the detrimental effect of low yield on the overall comparative ranking under the FU_{mass} —and its potential impact on farmers' livelihoods—we suggest that the manager of *orchard O* either abandon or adjust the current grass cultivation strategy and consider adopting mechanical clean cultivation to improve yield performance.

4.7 Fruit bagging techniques: paper bags, plastic bags, polyester mesh bags

Fruit bagging is a preharvest horticultural technique in which individual fruits or fruit clusters are enclosed in protective bags while still attached to the plant. This method is employed to shield fruits from pests, pathogens, and environmental damage, while also enhancing their external appearance and marketability (Buthlezi et al. 2021). However, fruit bagging also has drawbacks, including increased labour requirements, a higher risk of fungal growth, and elevated greenhouse gas emissions (Ding et al. 2024; Boerner 2024).

Compared with single-layer fruit bagging, double-bagging has been shown to reduce the fruit cracking rate of sugar apples during harsh winters that occasionally occur in Taitung (Chiang and Lu 2013). By helping immature sugar apples retain heat, double-bagging reduced fruit cracking and increased yield. Among various double-bagging options, the use of paper bags in combination with plastic bags resulted in the lowest fruit cracking rate (Chiang and Lu 2013).

In this study, all surveyed orchards adopted single-layer fruit bagging, except for *orchards CI*, *N* and *S*, where double-bagging was implemented during the winter production cycle. Compared with *orchard O*—another organic production system—the yields per unit area in *orchards N* and *S* were 38 and 44% higher, respectively (Table 5). Although

other factors may have contributed to these differences, double-bagging appears to be a promising practice for yield enhancement.

Notably, among the three orchards adopting winter double-bagging, *fruit bagging materials manufacturing (FBM)* was identified as a hotspot only within the *land use (LU)* impact category in *orchard N* (Table 3). In contrast, none of the impact category-level hotspots in *orchard S* were associated with *FBM* (Table 3). These results suggest that double-bagging, especially done with paper and plastic bags during harsh winters may be an effective strategy for improving yield and, consequently, reducing environmental impacts when evaluated using the FU_{mass} . Nevertheless, the managers of *orchards N* and *S* reported increased labour demands for bagging and unbagging of plastic bags, suggesting the need for further research using *life cycle costing (LCC)* to assess the economic viability and overall sustainability of double-bagging practices.

4.8 Fruit thinning strategy and crop load management

Fruit thinning is a horticultural practice involving the removal of a portion of immature or excess fruits during early developmental stages to regulate crop load, improve fruit size and quality, reduce physiological stress, and mitigate biennial bearing (Nautiyal et al. 2022; Dennis 2000). However, it is also associated with high labour and operational costs, and risks of over- or under-thinning (Dennis 2000; Marini 1996; Link 2000). Thinning methods vary by crop and include manual, mechanical, and chemical approaches. For apples, mechanical methods such as the Darwin string thinner have shown to reduce labour input while enhancing fruit quality (Schupp et al. 2008). In contrast, crops like peaches are primarily thinned manually due to limited effectiveness of mechanical or chemical alternatives (Costa and Vizzotto 2000; Greene and Costa 2012). Similarly, for tropical fruits such as mango, undesirable outcomes from chemical thinners necessitate manual thinning (Yeshitela et al. 2004). In Taiwan, sugar apple thinning is conducted manually using shears, likely due to the lack of crop-specific chemical thinners and the precision offered by manual methods.

Thinning directly influences crop load—the number of fruits retained on a tree to ensure proper development. In this study, crop load varied from 30 fruits per tree in *orchard C3* to 70 in *orchard C2* (Table 5). The low crop load in *orchard C3* contributed to its second-lowest yield and third-poorest environmental performance under the FU_{mass} (Tables 5 and 2). One potential strategy to improve the environmental performance of *orchard C3* is to initiate cultivation during the summer production cycle, which is currently not utilised.

This could increase the annual yield and enhance its overall ranking under the FU_{mass} . However, concerns about reduced fruit quality during the summer season have led the orchard manager to refrain from cultivating during this period. If these quality concerns can be effectively addressed, summer cultivation may offer an opportunity to improve both yield and environmental performance.

4.9 Policy relevance and implications

The findings of this study have practical relevance for Taiwan's ongoing efforts to promote sustainable agriculture through organic and low-input production systems. In particular, the empirical evidence demonstrating lower environmental burdens under reduced fertiliser application and natural farming aligns with Taiwan's Organic Agriculture Promotion Plan (2024–2027) (OAPP), launched by the Executive Yuan in August 2024 (Ministry of Agriculture [MOA] 2025b). This regional initiative aims to create an agricultural ecosystem that protects both environmental and public health while advancing Taiwan's transition toward net-zero carbon emissions (Department of Information Services 2025).

OAPP outlines nine key performance indicators (KPIs) to guide the development of the organic agriculture sector. These include targets for organic production area, market and export growth of organic products, animal-friendly livestock systems, certified aquaculture, and greenhouse gas reduction. Notably, it also calls for the development of quantitative valuation indicators for ecosystem services and lower greenhouse gas emissions from farming activities (MOA 2025b).

This study supports several of these KPI goals. The demonstrated environmental benefits of lower-input systems—such as reduced synthetic fertiliser use—correspond to the plan's GHG reduction and ecosystem service targets. Additionally, practices such as manual weeding, organic fertiliser substitution, and the use of organically certified materials (bio-fertilisers, biocontrol agents, and organically certified pesticides) are consistent with the plan's emphasis on soil health and public safety. While strategies such as year-round cultivation and winter double-bagging were primarily associated with yield improvements rather than environmental outcomes, they may support economic viability—an essential factor in the long-term adoption of organic farming practices. Therefore, these results offer evidence-based guidance that can inform the implementation of Taiwan's regional strategy for organic agriculture.

Table 6 Comparison of three tropical and subtropical fruit varieties—sugar apple, mango, and banana—based on previous cradle-to-orchard-gate life cycle assessment (LCA) studies, using 1 kg of harvested fruit as the functional unit. Bolded values indicate the highest impact within each environmental category

	Produce	Sugar apple	Sugar apple	Mango	Banana	Banana	Citrus	Citrus
	Cultivation method	organic	conventional	conventional	conventional	conventional	organic	conventional
	Country of production	Taiwan	Taiwan	Taiwan	Ecuador	Ecuador	Mexico	Mexico
	Year of study	2021–2024	2021–2024	2012–2015	2019	2020	2020	2020
GW	kg CO ₂ eq	1.04E+00	1.11E+00	1.91E-01	1.94E-02	2.20E-02	1.23E-01	0.03632
SOD	kg CFC11 eq	2.57E-05	2.16E-05		1.06E-05	1.22E-05	6.15E-09	5.23E-09
IR	kBq Co-60 eq	1.22E-02	1.49E-02					
OFH	kg NO _x eq	2.84E-03	2.83E-03					
FPM	kg PM _{2.5} eq	8.11E-03	5.11E-03	4.40E-04	3.89E-01	5.37E-01		
OFT	kg NO _x eq	2.90E-03	2.89E-03	5.10E-04	4.72E-01	5.44E-01		
TA	kg SO ₂ eq	3.53E-02	2.19E-02	1.04E-03	2.14E+00	3.13E+00	6.50E-04	0.00039
FeU	kg P eq	2.47E-03	2.65E-03	3.94E-03	1.19E-02	1.36E-02	5.10E-04	0.00038
MEu	kg N eq	6.00E-05	8.03E-05	5.69E-05	1.02E-01	1.38E-01		
TE	kg 1,4-DCB	1.59E+00	1.62E+00	6.44E-03			2.42E-02	0.00018
FEc	kg 1,4-DCB	5.81E-03	1.66E-02	2.48E+00 ^a				
MEc	kg 1,4-DCB	8.32E-03	1.58E-02					
HCT	kg 1,4-DCB	6.25E-03	7.80E-03	7.27E-09 ^b			1.01E-02	0.00832
HNC	kg 1,4-DCB	3.11E-01	3.77E-01	4.37E-08 ^b				
LU	m ² a crop eq	1.02E-01	8.14E-02	6.92E-02				
MRS	kg Cu eq	1.22E-04	3.43E-03					
FRS	kg oil eq	0.10	1.71E-01		3.06E-01	3.66E-01		
WC	m ³	2.08E-03	5.81E-03	4.02E-01				

^aThe unit used for *freshwater ecotoxicity* in the corresponding study was *comparative toxic unit for ecotoxicity* (CTUh)

^bThe unit used for *human carcinogenic toxicity* (HCT) and *human non-carcinogenic toxicity* (HNC) in the corresponding study was *comparative toxic unit for human health* (CTUe)

4.10 Comparison with the other tropical and subtropical fruits

To contextualize the environmental performance of sugar apple, results from “cradle-to-orchard-gate” LCA studies on mango (Taiwan), banana (Ecuador), and citrus (Mexico) were used for comparison. Only three impact categories—global warming potential (*GW*), terrestrial acidification (*TA*), and freshwater eutrophication (*FeU*)—were consistently assessed across all studies and thus selected for evaluation. As summarized in Table 6, organic sugar apple exhibited the highest impact in *GW*, whereas banana showed the highest impacts in *TA* and *FeU*. For *TA* and *FeU*, sugar apple and citrus occupied intermediate rankings.

These comparative results highlight both the relative environmental strengths of sugar apple and the areas where further improvements are warranted. Although sugar apple performs more favourably than banana in *TA* and *FeU*, its comparatively high *GW* underlines the need for targeted mitigation strategies to enhance the overall sustainability of sugar apple production.

5 Conclusion

This study presents the first detailed life cycle assessment of sugar apple (*Annona squamosa*) production in Taiwan, based on seven orchards representing a spectrum of cultivation strategies. By separately applying mass- and area-based functional units, it provides a comprehensive evaluation of environmental trade-offs across conventional, semi-organic, organic, and natural farming systems. Fertiliser use and production, packaging material manufacturing, and energy generation consistently emerged as key environmental hotspots. Freshwater eutrophication dominated most orchards due to nutrient losses from fertiliser application, whereas human carcinogenic toxicity prevailed in the natural farming orchard because of corrugated cardboard packaging. System-level comparisons showed that the natural farming system, characterised by minimal or low-impact inputs, achieved the lowest impacts overall. Aggregated by system category, the organic group generally outperformed the conventional group under the area-based functional unit; however, under the mass-based functional unit, the organic category showed higher impacts in 6 categories, driven primarily by fertiliser use, upstream paper related material inputs, and energy generation. These results underline the importance of accounting for upstream burdens and

avoiding burden shifting when evaluating lower-input or organic fruit systems.

Agronomic practices—including fertiliser or bio-fertiliser application, pest control strategies, fruit bagging, orchard floor management, and crop load regulation—substantially influenced yields and impact profiles. For example, reduced fertiliser application in *orchard C4* improved nutrient use efficiency without lowering yield, while high yields in the natural farming orchard improved performance under the mass-based functional unit. Bio-fertilisers and organically certified pest control materials contributed minimally to overall environmental impacts, except for freshwater eutrophication in *orchard N* under higher bio-fertiliser application rates, indicating their potential as lower-impact options for organic production systems. Limitations of this study include the small sample size, exclusion of irrigation water from the inventory, and reliance on secondary data for some upstream processes, introducing uncertainty and warranting cautious interpretation.

By incorporating two distinct functional units, providing detailed process-level resolution, and including thorough organically certified inputs in the life cycle inventory, this study makes a methodological contribution to LCA research on perennial fruit systems. The results support Taiwan's Organic Agriculture Promotion Plan (OAPP, 2024–2027), highlighting the feasibility of fertiliser use reduction and sustainability-oriented management strategies, including organically certified inputs. Future research should expand orchard sampling, integrate irrigation water use, and apply life cycle costing to improve the robustness and policy relevance of sustainability assessments for tropical fruit production.

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Data availability All data supporting the findings of this study are available within the paper and supporting information.

Declarations

Conflict of interest The Authors declare no competing interests.

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