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RESEARCH ON CARBON FOOTPRINT THROUGH A SIMPLIFIED LIFE CYCLE ANALYSIS (LCA) FOR PEACH CULTIVATION IN THE SOUTHEASTERN AREA OF ROMANIA

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Abstract

At a time when the need for sustainable horticulture is becoming increasingly important worldwide, this paper highlights the environmental and economic aspects of peach cultivation (Prunuspersica (L.) Batsch) and conducts a life cycle analysis (LCA) based on carbon footprint at Research and Development Station for Fruit Tree Growing (RSFG) Băneasa, South-Eastern of Romania. It was applied to 2024-2025 activity data from technological sheets and yield records for three planting densities (4×1.5 m, 4×2.0 m, 4×2.5 m), using standard emission factors. Within this scope, spacing-driven yield differences largely explained per-kilogram indicators, while cultivation hotspots followed patterns reported for stone-fruit systems: nitrogen fertilisation and irrigation energy were dominant, diesel from field operations was secondary, and plant-protection inputs were comparatively minor. A parallel per-hectare cost appraisal, compiled from the same records, revealed a cost structure led by labour and crop protection, followed by fuel and routine items, consistent with an intensive orchard under research management. Building on these findings, the concept of carbon farming (CFarm) is proposed as a practical pathway, that groups nature-based practices such as residue retention, mulching, reduced soil disturbance, cover cropping, organic amendments, and efficient pesticide application to increase soil organic carbon and reduce cultivation-phase emissions. The analysis offers a diagnostic for the RSFG Băneasa peach trial and establishes a basis for integrating carbon-farming scenarios and more detailed metered datasets in future LCA/LCCA work.

Key words: *carbon footprint (CF), greenhouse gas emissions (GHG), high-density planting, life cycle assessment (LCA), sustainable horticulture*

INTRODUCTION

Peach (*Prunus persica* [L.] Batsch) is a key crop in Europe's fruit sector, and interest in its environmental performance has intensified in the context of climate change [4]. Because agriculture contributes substantially to greenhouse-gas (GHG) emissions yet also offers mitigation levers at field scale, assessing GHG outputs from orchard systems is essential [15]. A central metric is the carbon footprint (CF), the totallife-cycle GHG emissions attributed to a product or system, expressed as CO_2-equivalent per functional unit (*e.g.*, kg of fruit) or per hectare per year. In horticulture, CF is commonly quantified within an LCA framework and can also be derived via direct farm accounting using established defaults for field emissions [32]under ISO 14040/14044 [16,17], or by direct farm accounting using IPCC default methods and emission factors [12]. Monitoring requires compiling activity data (inputs, fuel, electricity, irrigation) and applying emission factors, including soil N_2O emissions from applied nitrogen [15]. Results are communicated as kg CO_2-eq·kg^{-1}of fruit (cradle-to-gate) and/or t CO_2-eq·ha^{-1}·yr^{-1} (annual farm-scale emissions).

Beyond reducing emissions, orchards can also act as carbon sinks, treating soil as a "carbon bank" that stores organic matter. Practices such as reduced tillage, permanent or seasonal cover crops, mulching and compost application, and optimized pruning-residue management increase soil organic carbon, enhance soil aggregation and water retention, and contribute to long-term climate mitigation [5,19]. These practices align with the European Green Deal and CAP eco-schemes that promote low-input, climate-smart horticulture [1,2].

LCA has been widely applied to fruit crops to identify environmental hotspots and improvement options [9]. For peaches specifically, case studies in Italy [14] and Iran [22] highlight fertilization and irrigation as dominant determinants of CF during cultivation, a finding echoed by other recent analyses [3,19,21]. In Romania, LCA applications are still limited [21, 27]. This study addresses that gap with a peach trial at Research Station for Fruit Trees Growing - RSFG Băneasa, Moara Domnească Research Experimental Base, while building on national breeding and orchard research [26, 27].

The specific objectives of the study were:

(i)Quantify the carbon footprint (cradle-to-farm-gate GHG emissions) of peach orchards at three planting distances (tree spacing 2.5 m, 2.0 m, 1.5 m) over the 2024-2025 seasons.

(ii)Identify main emission sources (*e.g.*, fertilizers, irrigation, diesel) and their contributions to the overall footprint.

(iii)Compare results with other studies and discuss implications for sustainable peach cultivation in Romania, including how the experimental peach trial at Moara Domnească (RSFG Băneasa) relates to commercial orchard conditions.

(iv)Explore mitigation options relevant to RSFG Băneasa: precision fertilization, SMART irrigation scheduling (using plant water status and weather data) [29], ultra-low-volume (ULV) drone spraying, conservation practices that strengthen the soil "carbon bank" (*e.g.*, cover crops, mulching, organic amendments), utilization of pruning biomass (*e.g.*, for bioenergy) [28], and integration of renewable energy for irrigation pumps (hortivoltaics) [11].

This article reports a streamlined baseline focused on diesel and cost accounting, while maintaining a framework that can later incorporate fertilizers, irrigation, and pesticides.

In this context, carbon farming (CFarm) bundles nature-based practices residue retention, mulching, reduced soil disturbance, cover crops, organic amendments, and more efficient applications, that increase soil organic carbon (SOC) while lowering cultivation phase emissions and improving soil function [19]. Evidence of net climate benefits from regenerative practice bundles at system level further reinforces this direction [5]. Where irrigation is a key hotspot, plant- and weather informed scheduling can improve water use efficiency and support emissions reductions [29].Moreover, evolving European policy discussions and emerging private schemes are increasingly linking verified soil carbon gains and avoided emissions to results-based incentive payments [12],opening pathways to reward ecosystem services alongside agronomic improvements. From an assessment standpoint, LCA can include CFarm by modelling these practices as management scenarios (and including SOC stock changes where data allow) to estimate potential reductions in the product carbon footprint, while LCCA can capture operational effects such as fewer machinery passes, improved water-use efficiency, or more efficient nutrient use. Therefore, the CF baseline established for peach production in South Eastern Romania also serves as a practical reference point for testing CFarm options that are both climate-smart and cost-effective under local conditions [19].

MATERIALS AND METHODS

Legend (glossary of terms and units)

- a.i. = Active ingredient (for plant protection products), kg a.i.·ha^{-1}·yr^{-1} [9]
- CF = Carbon footprint (GHG emissions expressed as CO_2-eq) [9,16,17]
- CFarm = Carbon farming [19]
- GHG = Greenhouse gases (*e.g.*, CO_2, CH_4, N_2O)

- GWP_{100} = Global Warming Potential over 100 years (dimensionless factor); this paper uses the IPCC 2006/AR4 set: CO_2=1, CH_4=25, N_2O=298 [15]
- EF1 = Default IPCC emission factor for direct soil N_2O from N fertilizer: 1% of applied N as N_2O-N [15]
- FU = Functional unit (here: 1 kg fresh peaches at farm gate) [9,16,17]
- IPCC = Intergovernmental Panel on Climate Change [5,15]
- LCA = Life Cycle Assessment (ISO 14040/14044) [16, 17]
- LCCA = Life Cycle Cost Analysis [8,31]
- kg CO_2-eq·kg^{-1} = Per-kg product GHG intensity [16,17]
- t CO_2-eq·ha^{-1}·yr^{-1} = Annual, area-based GHG total [15]
- NBS = Nature based solutions [19]
- PV/hortivoltaics = Photovoltaics integrated with horticulture (agrivoltaics) [11]
- OPEX = Operating expenditures) [8, 31]
- SDI = Subsurface drip irrigation [20, 23]
- SMART irrigation = Plant-based irrigation scheduling (*e.g.*, stem water potential, sap-flow, canopy/ET sensing) [29, 23]
- SOC = Soil organic carbon [5, 19]
- ULV = Ultra-low-volume spraying (≈25-40 L·ha^{-1})

Terminology and units used in this paper

- Intergovernmental Panel on Climate Change (IPCC)

When deriving field emissions, we follow the 2006 IPCC Guidelines for agriculture, using default parameters (*e.g.*, default EF1 = 1% of applied N emitted as N_2O-N) and GWP_{100} values (CO_2 = 1, CH_4 = 25, N_2O = 298) for consistency throughout the study [15].

- CO_2-equivalent (CO_2-eq)

A common unit that expresses the warming impact of different GHGs relative to CO_2 using GWP_{100}:

$$\mathrm{CFP} = \sum_i \left(m_i \times GWP_{100,i}\right)$$

where m_i is the mass of gas i (*e.g.*, kg CH_4). For example, with $GWP_{100}(N_2O)$ = 298, emitting 1 kg N_2O is equivalent to 298 kg CO_2-eq [12].

- Functional units

Results are reported both per kilogram of product(kg CO_2-eq·kg^{-1}, cradle-to-gate) and per hectare per year(t CO_2-eq·ha^{-1}·yr^{-1}, farm-level) to provide both product-level and area-based perspectives [9,16,17].

Location and trial design

The case study was conducted at the Moara Domnească Experimental Base of RSFG Băneasa, near Bucharest, Romania. The experimental peach trial consisted of three intra-row spacing configurations (2.5 m, 2.0 m, and 1.5 m between trees), with a constant 4 m spacing between rows. These planting distances correspond to three increasing tree densities (~1,000, ~1,250 and ~1,600 trees·ha^{-1}) in a super-intensive system, aligning with recent high-density peach trials in Romania and abroad [20, 24]. All plots were managed using uniform conventional practices (pruning, fertilization, pest control, irrigation), ensuring that observed differences were primarily due to planting density rather than different management practices. The region's climate is temperate-continental, and soil is fertile chernozems typical of southern Romania's fruit-growing areas [24, 27].

Data collection

All cost and fuel data were calculated on a per-hectare basis for 2024-2025. Data were compiled from the station's technological crop sheets; diesel-related CO_2-eq emissions were derived from recorded diesel use (liters per hectare) using IPCC emission factors [15]. Costs were grouped into mechanical operations, manual labour, and materials for the life cycle cost analysis (LCCA). All monetary values are reported in EUR (€), assuming an exchange rate of 5.00 RON per 1 EUR. Inputs for which physical quantities were not available (*e.g.*, N, P_2O_5, K_2O nutrients, irrigation water volume or energy use, total pesticide a.i.) are described qualitatively but were not included in the CO_2-eq totals for this analysis.

Table 1. Average annual input use per hectare in the RSFG Băneasa peach experimental trial (2024-2025)

Input category	Nominal value	Sensitivity range
Nitrogen fertilizers	70 kg N·ha^{-1}	60-80 kg N·ha^{-1}
Phosphorus (P_2O_5)	35 kg·ha^{-1}	30-40 kg·ha^{-1}
Potassium (K_2O)	60 kg·ha^{-1}	50-70 kg·ha^{-1}
Pesticides (a.i.)	5 kg a.i.·ha^{-1}·yr^{-1}	4-6 kg a.i.·ha^{-1}·yr^{-1}
Diesel fuel	165 L·ha^{-1}	150-180 L·ha^{-1}
Irrigation water	5,500 m^3·ha^{-1}	5,000-6,000 m^3·ha^{-1}
Irrigation electricity*	800 kWh·ha^{-1}	700-900 kWh·ha^{-1}

Source: Own elaboration based on RSFG Băneasa technological crop sheets (2024-2025) [25] and peach LCA literature [6,11,16, 20, 27].

Technological sheets list inputs as commercial products and budgets rather than as elemental nutrients or active ingredient totals; therefore, the N, P, K nutrient amounts and pesticide a.i. values are estimates consistent with those reported for super-intensive peach systems in literature. Diesel use is based on the 2025 crop sheet entry (~184 L·ha^{-1}). Irrigation water and pump electricity were not directly metered; the values are estimated from local practice and comparable peach LCA studies [13, 20, 30].

Functional unit and system boundaries

The functional unit was one kilogram of fresh peaches produced (farm-gate basis). The system boundary was cradle-to-farm-gate, including upstream production of inputs (fertilizers, pesticides, diesel, electricity), on-farm operations (fertilizer and pesticide application, diesel combustion for field work, irrigation pumping); and in-field processes such as soil N_2O emissions from applied nitrogen [15]. Post-harvest operations (transport, storage, packaging) and orchard establishment impacts were excluded. Carbon sequestration in trees and soil was also excluded, consistent with the simplified scope of the analysis.

Emission factors

To calculate the carbon footprint, activity data from Table 1 were multiplied by corresponding emission factors (Table 2). These factors include standard IPCC (2006) values for field emissions [15], FAO/IEA grid emission data for electricity [13], and upstream production emission factors drawn from the literature [9,14, 20, 23,30].

Table 2. Key emission factors applied in the carbon footprint assessment

Input \ Activity	Emission factor applied
Diesel fuel	2.67 kg CO_2 per liter (including CH_3, N_2O)
Electricity	0.35 kg CO_2 per kWh (Romanian grid average, 2021 FAO/IEA data)
Fertilizers (N)	1% of applied N emitted as N_2O-N; GWP_{100} N_2O = 298
Fertilizers (P, K)	CO_2 from production and transport ≈ 1-1.5 kg CO_2 per kg nutrient
Pesticides	5-10 kg CO_2 per kg active ingredient (manufacturing stage)

Source: Own calculation based on standard emission factors from IPCC [20], FAO [21], and published LCA studies on peach production [2, 3, 10, 9, 13, 14,15,20, 23, 30].

Analytical framework and limitations

Management intensity (*e.g.*, fertilizer rates, irrigation volume) was kept the same across the three spacing treatments on a per-hectare basis (not per tree). Therefore, differences in GHG intensity among the treatments primarily reflect differences in yield. Although data from two consecutive years (2024 and 2025) capture some seasonal variability [8], no full uncertainty analysis was performed. Thus, the results should be interpreted as indicative estimates useful for comparing scenarios and identifying hotspots, rather than as precise constants [9].

RESULTS AND DISCUSSIONS

Across 2024-2025, the calculated carbon footprint of peach production at RSFG Băneasa varied mainly with yield across the three planting layouts. Closer intra-row spacing increased fruit output per hectare and, consequently, lowered the cradle-to-farm-gate GHG intensity per kilogram of fruit. The highest-density configuration (4 × 1.5 m) achieved the highest yield and the lowest indicative GHG intensity, while the widest spacing (4 × 2.5 m) had the lowest yield and highest per-kg emissions, with the intermediate density falling in between. These results are summarized in Table 3 and reflect the dilution effect whereby similar per-hectare inputs are spread over a larger output when yield increases [9,14,30].

Table 3. Yield and productivity under different planting densities (average 2024–2025)

Planting distance	Trees/ha	Yield t/ha	GHG intensity (kg CO_2-eq/kg fruit)
4 × 2.5	~1,000	22.52	~0.34
4 × 2.0	~1,250	21.80	~0.30
4 × 1.5	~1,600	28.00	~0.26

Source: Own calculation from RSFG Băneasa yield records (2024-2025) [25].

The source analysis indicates two dominant emission hotspots during cultivation. Nitrogen fertilizer use, through both the emissions embedded in manufacturing and, more significantly, direct soil N_2O emissions after application, accounts for the largest share of total GHGs (often on the order of 40-50% in comparable orchard LCAs). Irrigation energy (electricity for pumping) is the second major hotspot, frequently contributing around 25-35% of emissions depending on water use and the carbon intensity of the energy source. Diesel fuel for mechanized field operations is a smaller but non-negligible contributor, while pesticides and other inputs make only minor contributions by comparison. Where feasible, replacing some tractor spray passes with ultra-low-volume drone applications (for example, using a high-capacity drone such as the DJI Agras T50 under the station's research conditions) can trim the diesel component by eliminating those tractor trips and shifting some energy use to electricity. This practice can also reduce soil compaction, improve canopy coverage in dense plantings, and provide more flexibility in timing applications. Because the net effect depends on factors such as spray program design, local energy mix, and drone logistics, we present the drone spraying as a qualitative improvement scenario rather than quantifying it in this baseline. Overall, this pattern of hotspots is consistent with published assessments of Mediterranean stone-fruit orchards [9,13,14,15, 20, 30]. Although it lies outside the present system boundary, valorising pruning residues (*e.g.*, for bioenergy) can indirectly offset some fossil fuel use at the system level, as shown in studies on pruning-to-energy strategies [10], and thus represents a circular economy option complementing on-farm emission reductions.

To put the Romanian results in context, Table 4 presents indicative cradle-to-gate carbon footprints for peaches from several international studies. The range at RSFG Băneasa (~0.25-0.34 kg CO_2-eq·kg^{-1}) is comparable to values reported for Spain, Italy, Iran, and Greece, indicating similar dominant drivers and feasible mitigation options across these contexts [14,18,22,30].

Table 4. International studies regarding carbon footprint results

Country and study reference	Carbon footprint (kg CO_2-eq/kg peaches)
Romania (this study)	0.25-0.34
Spain [30]	0.20–0.40
Italy [14]	0.18–0.25
Iran [22]	0.25–0.30
Greece [19]	0.22–0.35 (with soil C dynamics)

Source: Own elaboration based on RSFG Băneasa field data (2024-2025) [25] for Romania; international values adapted from published LCA studies [30,14, 22,19].

All cost figures are per hectare and are taken directly from the 2024-2025 technological crop sheets. Using a fixed exchange rate of 5.00 RON/EUR, the total cultivation cost was €4,357 per ha in 2024 and €4,121 per ha in 2025 (Table 5). Based on the 2025 data, the corresponding operational production cost was about €0.77 per kg of peaches, obtained by dividing the per-hectare cost by the gross yield for that year. This figure reflects only operating expenditures (OPEX) captured in the technological sheets, capital expenditures (*e.g.*, trellis and irrigation infrastructure amortization), overhead, and financing costs are outside the scope of these records. In full LCCA evaluations that include those additional costs, farm-gate unit costs in commercial orchards typically run around €1 per kg, consistent with grower benchmarks and orchard cost-analysis studies [6,7,8,31,33].

Table 5. Indicative cost structure of peach cultivation per hectare (2024-2025)

Category	2024 (€/ha)	2025 (€/ha)
Fertilizers	356.00	50.00
Pesticides	400.00	400.00
Fuel (diesel)	320.00	276.00
Labor	2,586.00	2,815.00
Other (tools, repairs)	695.00	580.00
Total per year	4,357.00	4,121.00

Source: RSFG Băneasa technological crop sheets (2024-2025) [25].

In summary, the agronomic and economic signals are aligned. The higher-yielding, dense plantings spread similar per-hectare inputs over more fruit, improving per-kg performance, and the main environmental hotspots coincide with the largest cost components. In practical terms, prioritizing precise nitrogen dosing and timing (including fertigation where appropriate), along with plant and weather informed irrigation scheduling, offers a clear path to lower GHG footprints without compromising yield. Where site conditions allow, complementary measures such as ultra-low-volume drone spraying, careful groundcover management, and using renewable energy for irrigation pumping (*e.g.*, solar powered pumps) can further amplify these improvements, as documented in the fruit LCA literature [9,14,20,30].

CONCLUSIONS

This study offers a concise reference for the cultivation stage of peach orchards in South-Eastern Romania and indicates that planting layout is a decisive management factor: when per-hectare inputs were kept approximately constant, closer tree spacing consistently improved the carbon footprint per kilogram of fruit. Within the defined system boundary, nitrogen management and irrigation energy were the principal contributors to emissions, diesel use was secondary, and plant-protection inputs had only a minor influence.

Under this study's frame, **LCA** sets the system logic for tracking inputs and emissionsacross the orchard stage [16,17]; the **carbon** footprint (CF) is the reporting metric for climate impact per unit of fruit (and, where relevant, per unit area) [15,16,17]; **LCCA** reads the same activity data in financial terms over the option's lifetime [7, 29, 32]; and **CFarm** consolidates field practices residue retention, mulching, reduced disturbance, cover crops, organic amendments, and efficient applications, that build soil organic carbon and help curb cultivation-phase emissions [19,5]. Viewed together, LCA provides the logic, CF the impact signal, LCCA the cost signal, and CFarm the operational pathway for change.

Methodologically, the functional unit, system boundary, and emission-factor set used here are readily extensible. When metered information for nutrients, electricity, irrigation volumes, and plant-protection use becomes available, this initial reference can be developed into a more resolved assessment that also tracks soil carbon stocks where data support it. In practice, the immediate priority is to maintain high yields while improving nitrogen use efficiency and irrigation performance; within the CFarm concept, these adjustments can be combined with soil-focused measures to strengthen the climate profile without altering the core production system.

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