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Life Cycle Analysis of Organic Vegetable Production in the Municipality of Pamplona, Norte de Santander

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ABSTRACT

This research attempted to provide a Life Cycle Assessment (LCA) of organic vegetable production in Pamplona, Norte de Santander, and to measure its environmental performance as well as help to promote sustainable agricultural activity in the area. It analysed the production phases of the vegetable crops produced in the 35 rural districts of the municipality which included cradle (soil preparation) to the gate (transportation to markets). The methodological approach was based on the ISO 14040:2006 and ISO 14044:2006. Moreover, multi-criteria decision-making methodology was adopted with the help of the Analytic Hierarchy Process (AHP). In this approach preference scales between 1-9 were used to compare organic and conventional production systems and rank the key components of environmental impact related to the farming practices. The findings show that the conventional systems of vegetable production have much greater anthropogenic effects than the organic systems. In particular, traditional practices are the reason behind a 14 percent increase in the Global Warming Potential (GWP) of CO₂ emissions, a 59 percent rise in the level of acidifying gases, and a 93 percent rise in causing ozone layer depletion. These effects are mostly linked to the high application of synthetic manure, pesticides, and agrochemical inputs. The results imply that the enhancement of the organic production systems via efficient utilization of bio-inputs, agricultural residues, and sustainable packaging materials can seriously decrease the burden on the environment and enhance the sustainability and resilience of the local agricultural systems.

Keywords: *Life Cycle Analysis, Organic Production, Food Security, Local Economic Development, Agricultural Sustainability*

INTRODUCTION

Life Cycle Assessment (LCA) of a good or service is a methodology that evaluates the environmental impact generated across all its production processes. However, it can also refer to a specific brand-name product, a generic product, product categories, product forms, or a competitor's cycle (Alhashim et al., 2021). Furthermore, the application of life cycle assessment to evaluate environmental costs in raw material production and emissions has become of great importance, especially because it is useful for evaluating potential environmental impacts of a product. Given the growing interest in climate change mitigation and the implementation of sustainable production practices, it is of interest to study the environmental profile of agricultural products (Duran et al., 2022; Fernández et al., 2022; Birkved and Hauschild, 2006; ICONTEC, 1997). Nevertheless, this assessment can be developed at a conceptual level, identifying significant footprint elements; at a detailed level with complex expert analysis; or at a simplified level using standard model templates (Sierra-Zamora et al., 2022; Solorzano et al., 2022).

LCA studies on agricultural products (vegetables) are justified because soil preparation, fertilization, and pest and disease control are emitters of greenhouse gases such as Carbon Dioxide (CO₂), Methane (CH₄), or Nitrous Oxide (N₂O), generated by the use of agricultural fertilizers and pesticides. Nonetheless, regarding the valuation of pesticide emissions from agricultural applications, an inventory tool has been developed that takes into account the (physicochemical and biological) properties of pesticide ingredients and field application conditions (Ferrero et al., 2021). This is especially relevant when the goal is to comply with Sustainable Development Goal 12, Responsible Consumption and Production, regarding the efficient use of natural resources; improvements in food production, storage, transport, and distribution; replacement of hazardous chemicals with sustainable technologies; prevention, reduction, recycling, and reuse of organic waste; and the adoption of sustainable agricultural practices (Fernández et al., 2022; Finnveden et al., 2009).

The objective of this research was to conduct a Life Cycle Assessment (LCA) of organic vegetable production in the municipality of Pamplona, Norte de Santander. The goal is to promote sustainable agriculture in the region through actions focused on determining the environmental impacts associated with each stage of the organic vegetable production life cycle, evaluating the efficiency of resources used from sowing to harvest, and identifying improvement opportunities within the supply chain to reduce environmental footprints.

Consequently, the research question is limited to determining: What is the environmental impact of organic and conventional vegetable production from cradle-to-gate? It identifies that low-production is defined as conventional given the time required for the regeneration of land exposed to agrochemical cultivation, with the aim of identifying milestones that require improvement to eliminate negative burdens and provide procedural enhancements through bio-input alternatives. This is particularly relevant because natural regeneration considers restoration goals and multiscale variables, allowing for an understanding of successional trajectories to optimize recovery efforts.

Theoretical Framework

The theoretical basis of this study is based on methodology of Life Cycle Assessment (LCA) that is a popular analytical tool of comparing environmental impacts of a product or production system in the context of its entire life cycle (Hurtado-M et al., 2022; ICONTEC, 2022). The LCA methodology allows determining and measuring environmental loads of extracting raw materials to the last stages of production and distribution methodically. In this context, a special focus is laid on the Life Cycle Inventory (LCI) that is associated with the collection and measurement of all the inputs and outputs of the product system (Ulloa-Murillo et al., 2022). The inputs are the materials, resources, and energy that get in the production process, and therefore the outputs are the emissions, waste, and other sources of energy or material that are put out in the system at any of the stages of the life cycle. The other important aspect of the theoretical framework is the Life Cycle Impact Assessment (LCIA), which strives to assess the effects of the environment that is caused by the inputs and outputs that were identified during the inventory phase. This step enables researchers to identify how agricultural practices impact on the environment into natural resources depletion, ecosystem degradation and the possible threats to human health (Kumar and Pant, 2023; Ilakiya et al., 2020). The LCIA helps to gain a better picture of sustainability of the agricultural systems of production by correlating the inventory data with the environmental impact indicators.

METHODOLOGY

Research Design and Scope

The study is positioned within the domain of environmental research, focusing on the assessment of the impacts of vegetable production systems. While initially framed as basic research, this classification is debatable given its emphasis on real-world environmental implications; therefore, it is more appropriately conceptualized as applied environmental research, as it seeks to generate practical insights for improving agricultural sustainability. Methodologically, the study adopts a quantitative design, enabling the measurement, comparison, and statistical analysis of variables related to organic and conventional farming practices. In terms of scope, it is descriptive, as it systematically characterizes agricultural patterns and associated environmental conditions in the municipality of Pamplona, Norte de Santander. The research follows a non-experimental design, with variables observed in their natural context without manipulation. Additionally, a deductive approach guides the study, linking established theoretical frameworks on sustainable agriculture and environmental assessment to empirical observations within the selected study area.

Data Collection Method and Instrumentation.

The main method of data collection applied in this study was a structured questionnaire to the vegetable farmers in the rural area of the municipality of Pamplona. The survey tool was based on measurement scales that were developed to measure the perceptions, practices and management strategies employed by the farmers in the organic and conventional vegetable production systems. In order to ascertain the reliability and consistency of the instrument, two-stage pilot testing was done. A pilot test was conducted with 14 farmers in total, and this number provided the opportunity to pre-test the survey questions and make changes. The second pilot

test was then administered to 30 farming households so as to perfect the instrument and ensure that it was reliable.

Population and Sampling Strategy.

The study employed a non-probability convenience sampling approach, wherein participants were selected based on their accessibility and willingness to participate. However, to enhance representativeness across the study area, this approach was complemented by proportional allocation by district. Specifically, once eligible farmers were identified within each rural district, the number of respondents selected from each locality was proportionally distributed according to the size of the farming population in that district.

The target population comprised 1,083 farms distributed across 35 rural districts in the municipality of Pamplona, Norte de Santander. The required sample size was determined using a standard formula for finite populations at a 95% confidence level and 5% margin of error, resulting in a final sample of 284 farms. The proportional allocation factor was calculated as:

Sampling fraction = $n/N = 284/1083 = 0.26$

This sampling fraction (0.26) was then multiplied by the total number of farms in each district to determine the corresponding number of respondents per locality. This combined approach ensured both feasibility in data collection and adequate geographic representation across districts.

Table 1: Population Sample Size by Village

N°	Rural District	Total	Sample
1	Alcaparral	16	5
2	Alto Grande	36	9
3	Caima	14	3
4	Chíchira	50	14
5	Chilagaula	30	7
6	Chínchipa	27	7
7	Cimitarigua	32	9
8	Cúnuba	25	7
9	El Alizal	27	7
10	El Escorial	18	5
11	El Naranjo	54	14
12	El Palchal	16	5
13	El Rosal	39	9
14	EL Totumo	16	5
15	El Zarzal	43	12
16	Fontibón	32	9
17	García	21	5
18	Iscaligua	27	7
19	Jurado	23	6
20	La Unión	52	14
21	Llano Castro	27	7
22	Monte dentro	97	25
23	Navarro	16	5
24	Negavita	43	12

25	Peñas	14	3
26	Sabaguá	39	9
27	Sabaneta Alta	25	7
28	Sabaneta Baja	21	5
29	San Agustín	18	5
30	San Francisco	36	9
31	Santa Ana	32	9
32	Tampaqueba	12	3
33	Tencalá	39	9
34	Ulagá Alta	12	3
35	Ulagá Baja	54	14
	Total	1083	284

Inclusion and Exclusion Criteria.

The inclusion and exclusion criteria were used to determine the participation in the study whereby the respondent was required to have the required knowledge and experience on vegetable cultivation. The inclusion criterion was that the farmers should have grown at least three out of the thirty-two identified vegetable crops in their farm lands. This was necessary so that respondents were with experience in such practices enough to give credible information about crop management practices. The exclusion criterion was that the participants were not able to distinguish well between organic and conventional production systems as the comparative analysis needed an understanding of the management practice that was related to each mode of cultivation.

To minimize potential selection bias, the study verified farmers' ability to distinguish between organic and conventional production systems before participation. This was done by assessing their knowledge of farming practices, certification status, and the types of inputs and management strategies they employed, ensuring that only farmers with clear experience in the respective production system were included in the sample.

Life Cycle Analysis Framework.

The study is based on a Life Cycle Assessment (LCA) of organic and conventional vegetable production systems across the 35 rural districts of Pamplona, Norte de Santander, following the principles and guidelines of ISO 14040:2006 and ISO 14044:2006. The assessment was conducted from cradle to gate, encompassing all agricultural activities from soil preparation to post-harvest, but excluding transportation to local markets. Key LCA components were systematically defined to ensure methodological transparency. The functional unit was set as 1 kg of harvested vegetable to standardize comparisons between production systems. System boundaries included soil preparation, input application (fertilizers and pesticides), planting, irrigation, pest and disease management, harvesting, and post-harvest handling. Environmental impact categories considered included global warming potential, eutrophication, acidification, and energy consumption, while the life cycle inventory (LCI) data were obtained from field measurements, farmer surveys, and secondary literature sources. This framework allowed a comprehensive quantification of the environmental impacts associated with each stage of vegetable production.

Analytic Hierarchy Process Decision-Making Model.

To ensure the validity of the Analytic Hierarchy Process (AHP) results, all pairwise comparisons were conducted by a panel of experts with experience in agricultural production and environmental assessment. The consistency of their judgments was evaluated by calculating the Consistency Ratio (CR) for each comparison matrix, with only matrices meeting the acceptable threshold ($CR \leq 0.10$) included in the analysis. This procedure ensured that the prioritization of environmental impact factors was reliable and methodologically sound.

Agricultural Production Stages Evaluation.

The comparative analysis aimed to evaluate and weight 32 horticultural crops grown in Pamplona. The evaluation encompassed various agricultural production processes, including soil preparation, crop establishment, crop management, harvesting, and post-harvest handling. The stages included specific technical standards such as site selection, soil conditioning, fertilization, seed and seedling selection, irrigation control, weed management, pest and disease control, pruning, harvesting, storage, and transport logistics. Using the Life Cycle Assessment framework and the Analytic Hierarchy Process (AHP), the study identified the relative level of environmental performance of organic and conventional horticultural production systems, as well as the production chain phases associated with the most significant environmental impacts. The preference scale values were established from empirical data collected directly in the field, quantifying variables such as input use, labor demand, and observed yields, and then calibrated within the PAJ matrix structure. Table 2 shows the Preference Scale Evaluation.

The preference ratings presented in Table 2 were determined through a combination of empirical data collected from farmer surveys, insights from relevant literature, and validation by expert judgment. This triangulated approach ensured that the ratings were both evidence-based and contextually relevant, enhancing the transparency and reproducibility of the methodology.

Table 2: Preference Scale Evaluation

Procedure	Organic Cultivation Rating	Conventional Cultivation Rating	Technical Justification
Soil Preparation			
Site Selection	7	5	Biophysical Characteristics and Bioclimatic Factors
Soil Conditioning	9	3	Land Clearing and Soil Analysis
Fertilization / Manuring	7	3	Organic Fertilization and Basal Mineral Fertilization
Crop Sowing / Crop Planting			
Seed Selection	9	3	Germination Capacity, Varietal Purity, and Hybrid Vigor
Seedling Selection	7	5	Seedling Architecture and Root Development
Direct Sowing / Direct Seeding	7	3	Soil Tilth, Moisture, and Temperature
Crop Care / Crop Maintenance			
Irrigation	9	5	Field Capacity, Permanent Wilting

			Point, and Monitoring
Weed Control / Weed Management	9	3	Crop Rotation, Organic Mulching, and Planting Density
Pest Control	9	3	Biological Control, Ethological and Physical Control, and Host Elimination
Disease Control			Microclimate Management, Drainage and Balanced Nutrition, and Bio-inputs
Pruning	7	5	Pruning Type, Execution Technique, and Biosecurity Protocol
Harvesting			
Collection / Gathering	9	5	Maturity Index Determination, Harvesting Protocol, and Logistics
Storage	7	3	Cold Chain, Relative Humidity, and Ventilation

RESULTS

Environmental Profile and Weighting of the Life Cycle Inventory

The comparative analysis aimed to evaluate and weight 32 horticultural crops grown in Pamplona. The evaluation encompassed various agricultural production processes, including soil preparation, crop establishment, crop management, harvesting, and post-harvest handling. The stages included specific technical standards such as site selection, soil conditioning, fertilization, seed and seedling selection, irrigation control, weed management, pest and disease control, pruning, harvesting, storage, and transport logistics. Using the Life Cycle Assessment framework and the Analytic Hierarchy Process (AHP), the study identified the relative level of environmental performance of organic and conventional horticultural production systems, as well as the production chain phases associated with the most significant environmental impacts. The preference scale values were established from empirical data collected directly in the field, quantifying variables such as input use, labor demand, and observed yields, and then calibrated within the PAJ matrix structure. Table 2 shows the Preference Scale Evaluation.

Life Cycle Impact Assessment and Statistical Validation

Life Cycle Impact Assessment (LCIA), using the cradle-to-gate approach—which considers everything from the extraction, transport, and conditioning of raw materials to production within the company—demonstrated structural differences between the production systems. Specifically, the bivariate analysis and the chi-square homogeneity test applied to the 284 sample plots yielded significant results ($\chi^2 = 48.35$, $df = 5$, $p < .001$). This confirms that the observed differences in environmental impacts are not random, but rather statistically related to the structure of the production system (organic versus conventional).

Soil Preparation and Crop Establishment Stage

The LCA impact analysis of the preparation and planting stages revealed that soil conditioning in the organic system scored 0.045 in the terrestrial eutrophication category, compared to 0.850 for the conventional system. This quantitative difference is explained by the elimination of excess

synthetic nitrogen (N) and phosphorus (P), which protects soil quality and local biodiversity. These impact metrics validate that operational optimization from soil preparation to post-harvest not only reduces the environmental footprint but is also a determining factor in achieving high yields and economic profitability.

Crop Care and Environmental Emissions

During the crop management phase, the life cycle inventory demonstrated that the organic system reduced atmospheric emissions to 68.53 kg–eq de CO₂ and 47.97 kg–eq de N₂O per ton of vegetables, compared to 105.21 kg–eq CO₂ and 73.65 kg–eq de N₂O per ton of vegetables emitted by the conventional system. In terms of soil and war impact, the conventional system generated a soil load of 1,189 mg*kg⁻¹ of toxic residues and consumed 23% more water resources. The complete elimination of agrochemicals in the organic system eliminates soil toxicity, although this environmental benefit entails an intensification of operational labor hours (32 hours/ha per month) required for pest monitoring and cultural control.

Resource Efficiency and Eco-efficiency Indicators

The comparative analysis aimed to evaluate and rank 32 horticultural crops grown in the residential area of Pamplona. The evaluation encompassed various agricultural production processes, including soil preparation, crop establishment, crop management, harvesting, and post-harvest handling. These stages involved specific technical standards, including site selection, soil conditioning, fertilization, seed and seedling selection, irrigation control, weed management, pest and disease control, pruning, harvesting, storage, and transportation logistics. Using the Life Cycle Assessment (LCA) framework and the Analytic Hierarchy Process (AHP), the preference judgments detailed in Table 3 were empirically derived from the quantitative results of the LCA inventory itself (e.g., differences in kilograms of emissions or liters of water). These numerical values were normalized and assigned to the Saaty scale to construct the pairwise comparison matrix. Under this hybrid approach, the study sought to identify the relative level of environmental performance of organic and conventional horticultural production systems, as well as to identify the phases of the production chain that are associated with the most significant impacts on the environment.

Table 3: Eco – efficiency Trends

Impact Dimension Type	Finding in Organic Production	Finding in Conventional Production
Greenhouse Gases (GHG)	Gas emissions generated from 32% in the synthesis and application of organic fertilizers (plant waste) in organic crops.	Gas emissions generated from 68% in synthesis and application of fertilizers in conventional transition crops
Resource Use / Resource Depletion	Irrigation efficiency (wilt point monitoring) of 77%	Water waste and 68% risk of chemical leaching
Operational Resilience	Use of crop rotation and beneficial cover crops of 93%	External dependence on petrochemical inputs of 84%

DISCUSSION

The environmental impact assessment using the Life Cycle Assessment (LCA) methodology in vegetable production in Pamplona allows for a contrast between the operational reality of organic and conventional systems against global sustainability requirements. The results obtained not only validate the proposed hypothesis but also deepen the understanding of environmental hotspots within the regional horticultural supply chain. This arises from the “need

to ensure that all human activities occurring in our daily lives are developed within the capacity limits of the environment. The divergence found in the Life Cycle Inventory (LCI) coincides with the findings of Mantilla et al. (2023), who emphasize the importance of studying the agricultural environmental profile to mitigate climate change. The technical superiority of the organic system—rated by farmers at level 9 (extremely sustainable) compared to level 3 (moderate) for the conventional system—suggests that dependence on agrochemicals is the primary factor of degradation in the region. As noted by Martínez and Hernández (2023), the quantification of emissions is crucial; in this sense, the conventional system in Pamplona acts as a critical emitter of Nitrous Oxide (N₂O) and Carbon Dioxide (CO₂), moving away from SDG 12 targets.

The crop care stage emerged as the milestone with the greatest impact. The drastic reduction of emissions in the organic system, thanks to the use of bio-inputs and ethological control, ratifies the utility of the inventory tools proposed by Mucha-Hospinal et al. (2020) by considering the physicochemical properties of the applied ingredients. While the traditional system negatively impacts the ecosystem, especially due to its role in the deterioration of the ozone layer and soil pollution in Pamplona aligns with responsible production through carbon sequestration and the protection of edaphic biodiversity. A fundamental finding in the discussion is the high water-use efficiency observed in organic plots. In these, wilting point and field capacity monitoring allow for irrigation management that optimizes the resource, in contrast to the water waste and risk of nitrate leaching detected in conventional management. This operational resilience of the organic model responds to the historical need raised by Pereyra and Vaira (2021) to find solutions to the limitation of raw materials and energy resources. Lower dependence on petrochemical inputs not only reduces the environmental footprint but also strengthens the farmer's economic security against the price volatility of synthetic fertilizers.

Notably, the collection and storage process is the point of greatest convergence between both systems. This indicates that, regardless of the cultivation method, cold chain infrastructure and transport logistics represent a shared technical challenge across the 35 villages of Pamplona. Improving these links is imperative to reduce food waste and enhance chain efficiency, thus complying with the conclusive interpretation of the LCA which seeks, according to ICONTEC (2022), to provide recommendations for strategic decision-making.

Ultimately, the transition toward organic production models should not be seen merely as an ethical alternative, but as a technical and engineering necessity for the restoration of ecosystem services in Norte de Santander. Because identifying key improvements in fertilization and soil management allows for the design of public policies that promote the use of bio-inputs. This ensures competitive and sustainable production throughout its initial stages.

Implications of the Study

The results of this study have significant implications on sustainability of agriculture, environmental control and regional development in Pamplona, Norte de Santander. To begin with, the outcomes reveal the environmental benefits of organic vegetable production systems showing that bio-inputs and ecological management practices produce a powerful effect on

minimum emissions of greenhouse gases, toxicity of soil, and water pollution as opposed to the conventional agricultural systems. These findings imply that policy makers and agricultural sectors ought to encourage interventions that will help farmers to shift to organic production systems by conducting training, providing financial aid as well as access to environmentally friendly farming technologies. The research offers useful insights into the local and regional agricultural planning by establishing the key points in the production process where the impacts on the environment are the most important. The fact that crop care stage is the primary environment hot spot shows that a significant improvement in eco-efficiency of vegetable production systems can be achieved through better pest management, enhanced fertilization methods, and enhanced irrigation efficiency. Also, the findings indicate the significance of enhancing logistical infrastructure especially the cold chain management and transportation systems to minimize the post-harvest losses and enhance supply chain sustainability.

Limitations of the Study

This research has several limitations that may be taken into account when one interprets the results although it has contributed to this. Among the main constraints is associated with the sampling technique applied in the research. The study used the non-probability convenience sampling method, which can be a limitation of the extrapolation of the results to a broader setting other than the one in the municipality of Pamplona. Even though the sample of 284 agricultural plots is a large percentage of the agricultural population in the area, the findings might otherwise not be true to the diversity of agricultural activities in other areas with different climatic, economic, or technological factors. The other weakness relates to the data collection procedure. The research was mostly based on survey data collected by responding farmers which could have subjective bias or inexistence of the study as a result of the different perceptions, knowledge, or recollection of the agricultural practices by the farmers participating in the survey. Although reliability tests like Cronbach alpha were used to maintain internal consistency and statistical analysis, self reported data can influence the accuracy of the environmental tests. Moreover, life cycle assessment was done in the form of cradle-to-gate wherein the production involved the processes up to storage and transportation to the markets. This led to the fact that downstream activities of distribution, retail, consumption and waste management were not considered in analysis. These stages would help give a more detailed assessment of the total environmental impact of vegetable production systems.

Future Research Direction

The workings of this study should also be further developed in future research, with the inclusion of more analytical angles and geographical areas. The first way it could be taken is the extension of the life cycle assessments past the cradle-to-gate point and into the entire life cycle of agricultural products that include distribution, retail, consumption, and waste management processes. This would offer a more in-depth view of the environmental impact of vegetable production systems and would enable the establishment of further avenues of enhancing sustainability along the entire food supply chain. The other notable field that can be used in future studies is the incorporation of economic and social sustainability metrics and the

environment. Although this research mainly concentrated on environmental effects of the organic and conventional agricultural systems, future research may involve research on other aspects like cost of production, farmers earnings, market reach, work terms and conditions, and consumer tastes and preferences. This would allow a more comprehensive assessment of the sustainability of agricultural production systems and contribute to the formulation of the policies that would support the environment protection without jeopardizing the economic feasibility of farmers.

CONCLUSION

This study shows that the organic vegetable production systems in the Pamplona municipality pose a much lesser environmental impact than the traditional farming methods. By using Life Cycle Assessment and the Analytic Hierarchy Process, the research was able to determine the major differences between the two systems at each of the soil preparation stage, crop establishment, crop care, harvesting and post-harvest management. According to the results, the traditional system produces a greater environmental load through the intensive use of synthetic fertilizers and pesticides that lead to greenhouse gases emission, soil erosion, and water pollution. Conversely, organic production systems enhance environmental friendly production practices that include application of bio-inputs, crop rotation, cover crops and effective management of irrigation. These activities not only help in minimizing the pollution of the environment, but also help restore the health of the soil, preserve the water resources, and reduce the effects of climate change by sequestration of carbon in the agricultural soil. The fact that the crop care stage was identified as the biggest environmental hot-spot also proves that the eco-efficiency of agricultural systems may be improved by improving the pest management and fertilization methods.

These findings align with global scientific evidence; in fact, research by Tuomisto et al. (2012), Reganold and Wachter (2016), and Muller et al. (2017) corroborates that organic systems significantly reduce environmental impact per unit area. These authors conclude that replacing synthetic agrochemicals with bio-inputs and crop rotation mitigates greenhouse gas emissions and prevents eutrophication. They also highlight that these practices promote carbon sequestration and soil health, positioning organic production as a key strategy in the face of climate change.

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