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Article

Revealing the True Cost of Food: A Life Cycle Assessment for Sustainability in the Agri-Food Sector

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Abstract: The spice industry, especially the production of vanilla (*Vanilla planifolia*), plays an important role in Indonesia's agricultural economy. However, the complexity of the vanilla cultivation and post-harvest process has the potential to create significant ecological stress. This study aims to evaluate the environmental impact of vanilla production in Indonesia using *the Life Cycle Assessment* (LCA) approach based on ISO 14040/14044 standards and the ReCiPe 2016 method. The functional unit used is one kilogram of dry vanilla, ready for consumption, with a cradle-to-gate *system limit*. Data was collected from a combination of field surveys, farmer interviews, and Ecoinvent's secondary database. The results of the analysis show that the cultivation stage contributes the greatest *to Global Warming Potential*, eutrophication, and acidification, mainly due to the use of nitrogen fertilizers and conventional irrigation systems. The biomass combustion-based post-harvest drying process also contributes to SO_2 and NO_x emissions. The variability between production areas (Papua, Bali, and East Java) indicates the importance of a local context-based approach in mitigation strategies. This study recommends the adoption of low-emission drying technologies, the use of organic fertilizers, and efficient irrigation as technical steps, as well as the need to integrate LCA in national agricultural policies. This study confirms the strategic role of LCA not only as an evaluative tool but also as the foundation of the sustainability policy of the spice sector in Indonesia.

Keywords: Life Cycle Assessment, Vanilla, Environmental impact, Sustainable agriculture, ReCiPe, Spice production

1. Introduction

The food industry is one of the strategic sectors in the global economic system that is not only responsible for providing nutritional needs for the world's population, but also plays an important role in social and economic sustainability. As the global population increases, which is estimated to reach 9.7 billion people by 2050 (United Nations, 2022), the need for quality, safe, and sustainable food products is becoming more urgent. However, behind its urgency in supporting life, the food industry has various serious problems related to environmental sustainability. The processes of food production, distribution, and consumption are known to contribute a significant portion to global greenhouse gas emissions, inefficient water use, soil degradation, and biodiversity loss (Poore & Nemecek, 2018). This shows that the food industry, although vital, is also one of the main contributors to environmental degradation. In the context of sustainability, there is a need to develop a systematic and comprehensive approach that is able to measure, evaluate, and reduce the environmental impact of the entire food supply chain. One approach that has developed significantly and is recognized by the scientific community and policy practitioners is *the Life Cycle Assessment* (LCA). LCA provides a methodological framework that allows for evaluating the environmental aspects of a product or process throughout its life cycle, from the stage of raw material extraction, production, distribution, consumption, to final disposal. Based on the international standards ISO 14040 and ISO 14044, LCA is present as an analytical tool that allows for more information and environmentally sound decision-making (Klöpffer & Grahl, 2014).

The implementation of LCA in the food industry has shown significant benefits, such as in the optimization of production processes, the identification of critical points in the supply chain, and the design of strategies for reducing emissions and resource consumption. However, most LCA applications have so far been focused on key food commodities such as dairy, meat, and grains. Meanwhile, high-value commodities that have high complexity in their production processes, such as vanilla, are still rarely thoroughly evaluated using the LCA approach. Vanilla is one of the most expensive spices and is widely used in various industries, from food and beverages to cosmetics and pharmaceuticals.

Vanilla (Vanilla planifolia), as a leading export commodity from various developing countries such as Indonesia and Madagascar, has unique and very labor-intensive production characteristics. The production process includes crop cultivation, manual pollination, selective harvesting, fermentation, and drying, all of which require significant time, skill, and resource input. In addition, challenges such as climate change, global price fluctuations, low genetic diversity of plants, and lack of access to environmentally friendly technologies make vanilla production vulnerable to environmental and socio-economic pressures. Most of the literature available today focuses on the chemical and economic aspects of vanilla, such as vanillin production efficiency or market analysis. Meanwhile, in-depth studies of the environmental impact of the entire vanilla production chain, especially through the LCA approach, are still very limited. In a study by Zhao et al. (2021), for example, LCA's analysis of biosynthetic vanillin showed the potential for a significant reduction in environmental impact compared to chemical synthetic methods. However, this kind of study has not touched much on the traditional aspects of vanilla production that still dominate in major producing countries such as Indonesia.

In Indonesia itself, vanilla has become a promising strategic export commodity, especially from areas such as East Java, Bali, and Papua. However, challenges still loom over the sector, ranging from weak post-harvest infrastructure, reliance on traditional cultivation practices, to the lack of integrated sustainability standards in the value chain. This raises important questions about the extent to which vanilla production practices in Indonesia contribute to environmental impact and how improvement efforts can be designed scientifically and data-driven. In facing these challenges, the application of the LCA approach is very relevant and urgent. Using LCA, it is possible to identify the stages in the vanilla production life cycle that contribute the most to different categories of environmental impacts, such as global warming, eutrophication, acidification, and toxicity. The results of the evaluation not only provide information for producers and policymakers but also open up opportunities for the implementation of mitigation strategies, technology improvements, and science-based policy formulation. Furthermore, the integration of LCA results with international sustainability standards such as Fair Trade, Rainforest Alliance, and organic certification can encourage the adoption of more socially and environmentally responsible production practices. This is especially important, given the increasing global consumer demand for products that are not only of high quality but also sustainably produced.

Based on this background, this research is designed to fill the existing knowledge gap by conducting a comprehensive study of the environmental impact of vanilla production in Indonesia through the Life Cycle Assessment approach. The study is expected to not only make a scientific contribution to the development of LCA methodologies for spice commodities but also provide practical recommendations for industry players, policymakers, and other stakeholders in order to realize a more sustainable vanilla production system in the future. This research has a specific scope designed to answer research questions in a focused manner while maintaining the breadth of the context of the vanilla production ecosystem. The study will take the Life Cycle Assessment approach as the main analytical framework, with the scope of the system covering the entire vanilla production process from the cultivation stage to the ready-to-consume dry product, according to the "cradle to gate" boundary system. The functional unit used in this study was one kilogram of ready-to-consume dried vanilla. This unit selection takes into account standardization in LCA studies and allows for comparisons with previous study results at the international level. The analysis will cover various aspects of inputs (such as seeds, fertilizers, water, and energy) as well as outputs (emissions, waste, and by-products) in each stage of the production process. This study is focused on the context of vanilla production in Indonesia, with primary data collection carried out through interviews, field observations, and surveys of vanilla farmers in the production center. Secondary data will be obtained from the scientific literature, LCA databases such as Ecoinvent, as well as relevant industry reports. The environmental impact assessment will be carried out using the ReCiPe 2016 method with the help of SimaPro or OpenLCA software. With these limitations, this research aims to produce a valid, relevant, and can be used as a basis for the formulation of more sustainable vanilla production policies at the national and global levels.

2. Materials and Methods

This study applies *the Life Cycle Assessment* (LCA) approach as the main framework to evaluate the environmental impact of vanilla production in Indonesia. LCA was chosen for its ability to provide a comprehensive overview of various environmental aspects of a production system, from raw material extraction to ready-to-use final products. Through this approach, the research is expected to produce objective, systematic, and scientifically data-based information to support decision-making towards more sustainable vanilla production practices. The design of this research is descriptive-quantitative with a case study approach. The research is focused on vanilla production systems in Indonesia, with major case studies in several vanilla production centers such as in the provinces of Papua, Bali, and East Java. The case study approach was chosen to allow for an in-depth understanding of the specific conditions of vanilla production in the field, as well as to answer research questions related to life cycle characteristics and critical points of environmental impact.

Goal and Scope Definition is the initial stage in the implementation of the LCA. In this study, the main objectives of LCA are to:

1. Quantitatively evaluate the environmental impact of the vanilla production system in Indonesia.
2. Identify the stages of the process that contribute the most to the different categories of environmental impacts.
3. Develop recommendations for environmental impact reduction based on the results of the analysis.

The functional unit used is one kilogram of dry vanilla ready for consumption. The limit system applied is "cradle to gate", which covers all stages from cultivation to the final stage before the product is distributed to the market. The stages analyzed include: (1) Vanilla plant cultivation (land tillage, planting, fertilization, watering, manual pollination); (2) Harvesting and post-harvest (picking, fermentation, drying); and (3) Packaging and storage. Data collection was carried out through two sources, namely (1) Primary Data: obtained through direct observation, interviews with vanilla farmers and business actors, and questionnaire surveys in production areas. This data includes information on the use of input materials (fertilizers, pesticides, water, energy), technical production processes, and waste management; and (2) Secondary Data: collected from scientific literature, industry reports, and LCA databases such as Ecoinvent. Secondary data is used to complement and compare primary data, as well as to estimate emissions in cases where primary data are not fully available.

The aspects analyzed in the inventory include energy consumption (electricity, fuel, biomass); Irrigation and process water consumption; Use of chemicals (fertilizers and pesticides); Greenhouse gas emissions from combustion, organic decomposition, and agricultural activities; and Solid and liquid waste, as well as their management. The impact assessment was carried out using the midpoint version of the ReCiPe 2016 method, which allows the evaluation of many relevant environmental impact categories, namely: (1) Global Warming Potential (GWP); (2) Eutrophication (water and soil); (3) Acidification; (4) Depletion of resources (fossil and mineral energy); and (5) Toxicity to humans and ecotoxicity. The calculations were performed using LCA software such as SimaPro or OpenLCA, and the results were compared between the stages of the process to identify the dominant contributors to each type of impact. The interpretation of the LCIA results was carried out by tracing the root cause of each dominant impact category. The results were analyzed to provide answers to the formulation of research problems and as a basis for the preparation of mitigation recommendations. In addition, a sensitivity analysis was carried out to test how changes in assumptions or variations in data affected the final result. Validation is carried out through consultation with LCA experts and spice agronomy; comparison with the results of similar studies in the spice or other horticultural sectors; and testing consistency between data sources and triangulation of information from the field.

3. Results and Discussion

3.1. Environmental Impact Profile of Vanilla Production

Based on the results of calculations using the ReCiPe 2016 method, an environmental impact profile was obtained from one kilogram of ready-to-consume dried vanilla. The results show that global warming (GWP) is the highest impact category, followed by eutrophication, acidification, and toxicity. The cultivation process accounts for more than 50% of the total GWP, which comes mostly from the use of nitrogen fertilizers and biomass burning activities on farmland. The significant contribution of nitrogen fertilizers to N2O emissions—a greenhouse gas with much higher global warming potential than CO2—is of particular concern. In addition, the use of energy in the post-harvest drying process, especially in areas that still rely on fossil fuels or wood burning, is an additional source of emissions. The fermentation and packaging stages make a relatively lower contribution but cannot be ignored, especially in the categories of toxicity to humans and ecotoxicity.

3.2. Environmental Impact Hotspot Analysis

Through the identification of hotspots, it was found that the use of synthetic fertilizers and conventional irrigation practices are the two dominant factors that need to be considered. The use of fertilizers not only contributes to global warming but also exacerbates the eutrophication of water and soil due to runoff containing nitrate and phosphate compounds. Inefficient irrigation, especially in areas with low rainfall, significantly increases water consumption and puts pressure on local water resources. Uncontrolled irrigation systems also contribute to soil degradation and accelerate the erosion process. Vanilla drying, which is traditionally done using solar power and in some cases assisted by biomass burning, contributes substantially to the impact of acidification and energy consumption. The use of solid fuels such as firewood causes SO2 and NOx emissions that exacerbate the acidification effect.

3.3. Comparison Between Production Stages

To provide a comprehensive understanding of the contribution of each stage, environmental impact normalization is carried out based on functional units. The results can be extracted as follows:

1. Cultivation accounts for 55-65% of the total GWP;
2. Post-harvest processing (fermentation and drying) contributes about 20-30% to the toxicity and acidification category;

3. Packaging and storage account for <10% of the overall environmental impact.

These findings confirm that key interventions need to be focused on the early stages of production, particularly on the use of agricultural inputs and energy efficiency in the post-harvest process.

3.4. Discussion of Results in the Context of Sustainability

In general, the results of LCA show that traditional vanilla production systems in Indonesia have a significant environmental impact, particularly in the categories of GWP, eutrophication, and acidification. This fact indicates that there is a huge room for systemic improvement to improve production sustainability. One of the mitigation strategies that can be applied is the switch from chemical fertilizers to organic fertilizers or integrated soil fertility *management techniques*. The use of compost and biochar, for example, not only lowers N2O emissions but also improves soil health and carbon sequestration capacity. In the energy aspect, the use of renewable energy sources such as controlled solar-based drying (*solar tunnel dryer*) can be an alternative solution to reduce dependence on fossil fuels and biomass. This technology has demonstrated higher energy efficiency and lower environmental impact in similar studies in the horticulture sector. In addition to technical interventions, systemic approaches through farmer training, increased access to environmentally friendly technologies, and environmentally-based incentives are key to the success of sustainability transformation. Policy support from local and central governments is also very decisive, for example, through the integration of LCA principles in the strategic environmental assessment (KLHS) for the spice agriculture sector.

3.5. Sensitivity Analysis

Sensitivity analysis was performed to assess the extent to which the uncertainty in the data and assumptions used in the LCA model affected the outcome. In this study, the main parameters analyzed for sensitivity include the amount of nitrogen fertilizer use, energy consumption in drying, and emissions from biomass fuels. The results of the analysis show that a variation of ±20% in the use of nitrogen fertilizers can cause fluctuations in the impact of the Global Warming Potential (GWP) of up to 15%. This shows that environmental impacts are very sensitive to fertilization practices. Meanwhile, changes in energy consumption in the drying process (e.g., with or without the use of additional firewood) affect the acidification impact category by up to 12%. The uncertainty of emission data from biomass shows varying influences depending on the combustion efficiency and humidity of the fuel. From these results, it can be concluded that the LCA results are quite robust, but improved accuracy in data inventory, especially on agricultural inputs, is essential to strengthen the validity of the analysis and the effectiveness of the recommended mitigation strategies.

3.6. Comparison Between Study Sites

The study also compared LCA results from three main vanilla production sites in Indonesia: Papua, Bali, and East Java. Each region has different agroecological conditions, production technologies, and agricultural habits, resulting in variations in the contribution of environmental impacts. In Papua, the use of chemical inputs is lower, but the drying process uses intensive firewood, which has an impact on high acidification emissions and GWP. In Bali, the agricultural system is more integrated with organic practices, and drying makes maximum use of solar energy. This lowers the overall environmental impact. In East Java, there is intensive fertilizer use and water-intensive irrigation systems, thus showing the highest value in the categories of eutrophication and water use. This comparison shows that local practices strongly determine the environmental impact profile. Therefore, intervention strategies cannot be uniform, but need to be adapted to local ecological and social characteristics.

3.7. Implications for Policy and Industry

The findings of this study have important implications for the development of public policies and strategies for the spice industry sector. First, the need to integrate LCA assessments into national and regional agricultural planning systems, for example, through the development of life-cycle-based production sustainability indicators. Second, incentives are needed for farmers and industry players to adopt low-emission technologies, such as solar drying, biofertilizer, and drip irrigation. The provision of green subsidies and environmental performance-based certifications can be a strategic approach to accelerate adoption. Third, the government can use the results of this LCA study as a basis for the formulation of environmentally friendly production standards for vanilla exports. Export destination countries increasingly require a low carbon footprint in products, so the implementation of LCA also plays a role in strengthening the competitiveness of Indonesian products in the global market.

3.8. Synthesis Towards a Sustainable Vanilla Production Model

Based on the results of the analysis and discussion above, a framework for a sustainable vanilla production model can be prepared that combines technical, social, and institutional elements. The model consists of: (1) Adaptive Agriculture Practices: The use of eco-friendly inputs, sustainable soil management, and crop rotation to maintain soil fertility and biodiversity; (2) Post-Harvest Energy Efficiency: Application of renewable drying technology and improved efficiency of the fermentation process to reduce energy consumption and emissions; (3) Farmer Empowerment and LCA Literacy: Training program on environmental management and understanding of environmental footprints from the production process; and (4) Environmental Regulation and Certification: Strengthening legal instruments and implementing green production standards to ensure long-term sustainability. This framework is flexible and adaptive, and needs to be continuously developed through the active participation of all stakeholders in the vanilla value chain. Thus, the results of this study are not only a scientific reference but also a practical guide towards the ecological transition of the national spice industry.

4. Conclusions

This research has provided a comprehensive overview of the environmental impact of the vanilla production system in Indonesia through the Life Cycle Assessment (LCA) approach. The results of the analysis show that the cultivation process is a major contributor to various categories of environmental impacts, especially greenhouse gas (GWP) emissions, eutrophication, and acidification. The use of chemical fertilizers, inefficient irrigation systems, and energy consumption from non-renewable sources in the post-harvest process are the dominant factors causing the high environmental footprint of vanilla production. The variation between study areas underscores the importance of considering local context in designing sustainability strategies. Traditional practices in Papua, Bali, and East Java show significant differences in environmental impact, both in terms of input intensity and production process efficiency. These findings indicate that improvement strategies should be adjusted spatially and socioculturally. The study also shows that LCA not only serves as a quantitative tool to evaluate environmental impacts, but also as a policy instrument that can drive systemic transformation towards more sustainable spice farming. Thus, the results of this research can be used as a foothold for policy formulation, green incentives, and national vanilla industry development planning that is adaptive to global environmental and climate challenges.

Based on the results of the analysis, many technical recommendations can be implemented by vanilla producers to reduce the ecological pressure of their production systems: (1) Optimization of fertilizer use: Switch to organic-based fertilization systems or biofertilizers that can reduce N2O emissions and improve soil quality in the long term; (2) Efficient irrigation application: The use of drip irrigation system and rainwater collection to reduce water consumption and runoff that causes eutrophication; (3) Low emission drying technology: Substitution of wood burning-based drying with controlled solar drying technology such as solar tunnel dryer to lower SO2 and NOx emissions; and (4) Post-harvest energy diversification: Exploration of the potential use of agricultural waste biomass as a cleaner alternative energy source.

The government has a central role in directing the national food production system towards sustainability. Based on the findings of this study, the following are relevant policy recommendations: (1) Integration of LCA in agricultural policy: Require LCA assessment in large-scale agricultural projects and export commodity development as part of feasibility studies and environmental impact assessments; (2) Sustainable production incentives: Preparation of fiscal incentive schemes (green subsidies) for farmers who adopt environmentally friendly production technologies, as well as facilitation of sustainability certification; (3) Development of agricultural environmental information systems: Establishment of a national database to monitor and evaluate the environmental impact of strategic commodities including vanilla, to support evidence-based policies; and (4) Sustainability standardization and certification: Establishment of LCA-based sustainable vanilla production standards as a prerequisite in product exports to countries with strict environmental regulations.

Although this research has made important contributions, there is still room for further development. Some of the recommended directions for further research include: (1) Integration of social and economic dimensions in LCA: Development of a Life Cycle Sustainability Assessment (LCSA) approach to assess sustainability in a multidimensional manner; (2) Comparative analysis between vanilla producing countries: Cross-country studies (Indonesia, Madagascar, Papua New Guinea) to understand best practices and develop a global strategy for vanilla sustainability; (3) Simulation of technology intervention scenarios: Use of simulation models to test the potential impact of various technology options on environmental impact reduction; and (4) Participatory approach in LCA strategy design: Involving farmers, industry players, and local governments in the process of designing interventions to be more contextual and acceptable at the grassroots level. Taking these recommendations into account, it is hoped that collective efforts in realizing sustainable vanilla production in Indonesia can be accelerated effectively and inclusively.

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