Comparative Life Cycle Assessment of Environmental Impacts and Economic Feasibility: Conventional versus Organic Tomato Cultivation in Northern India

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Abstract

To meet the growing demand for vegetable production and promote sustainable agriculture, it is imperative to implement effective input management and adopt eco-friendly farming practices. This study aims to compare the environmental impacts of conventional and organic tomato cultivation in the northern plains of India. This study utilizes SimaPro 9.1.1 software for a comprehensive cradle-to-farm gate Life Cycle Assessment (LCA), assessing production stages, identifying key environmental factors, and incorporating ReCiPe Midpoint and Endpoint methods with one-hectare as a functional unit. Findings reveal that conventional cultivation is more affected by fertilization and transplanting, while organic cultivation emphasizes transplanting and irrigation. Organic cultivation contributes 904.708 kg CO₂ while conventional cultivation contributes 1307.917 kg CO₂ to Global Warming potential. Switching to organic cultivation leads to a significant 35.04% decrease in all impact categories. Using the endpoint method, organic cultivation achieves a notable 27.16% reduction, scoring 58.30 compared to conventional cultivation's 80.04. The LCA analysis of tomato cultivation highlights fertilization as the predominant environmental concern, emphasizing the need for sustainable techniques to minimize waste and mitigate environmental impacts. This study recommends imposing restrictions on fertilizer and pesticide use, and formulating effective policies to promote the adoption of sustainable practices.

1. Introduction

Agriculture, being a multifaceted and intricate system, gives rise to substantial environmental strains, spanning from the depletion of natural resources to the generation of waste. These burdens predominantly emanate from the widespread adoption of intensive agricultural practices and the application of novel techniques. The agricultural sector plays a crucial role as the first step in the food supply chain, encompassing impact categories such as ecology, geography, soil characteristics, erosion, and freshwater ecosystem. Agriculture production needs massive quantities of capital such as water, fossil fuels, and agrochemicals, whose utilization degrades the ecosystem in various ways. Excessive pesticide use leads to greenhouse gas emissions and water pollution. In India, freshwater resources are being polluted through drainage and leaching of nitrates from agricultural land and the overuse and misuse of chemical pesticides. All of these challenges are closely tied to the fundamental aspect of food safety, prompting extensive societal discussions on how best to address these concerns globally. The United Nations has also included health and food security as a top priority among its Sustainable Development Goals and established various targets to address this issue using existing resources. Additionally, emissions arising from agricultural activities demonstrate high variability due to factors such as local climate, soil quality, agricultural practices, and numerous interconnected elements.

In recent years, there has been a notable increase in global demand for organic crops due to consumer preferences for healthier and more sustainable food choices. A compelling meta-analysis, based on an examination of 343 peer-reviewed publications, highlighted that organic crops tend to have higher concentrations of antioxidant compounds, lower levels of cadmium, and reduced incidence of pesticide residues in their edible parts compared to non-organic crops. However, it is important to note that consumers often lack access to reliable information regarding the true environmental impacts of organic farming, as well as other cropping systems. Consequently, comprehensive studies encompassing various crops are necessary to verify whether the promised benefits of enhanced sustainability and reduced greenhouse gas (GHG) impacts associated with organic farming are genuinely realized or not.

Considering the present scenario, it is essential to satisfy the escalating need for vegetable production while also promoting sustainable agriculture. This necessitates the implementation of an effective approach to manage inputs and adopt eco-friendly farm practices. A substantial amount of research has been undertaken and is still in progress to assess farming practices and investigate the overall environmental impact of agriculture, employing diverse methodologies. Among the variety of evaluation methods, life-cycle assessment (LCA) is known to be one of the most informative tools for evaluating the environmental impacts of farm products. LCA offers a holistic methodology to analyze the environmental impacts associated with a product across its complete life cycle. Figure 1 showcases the typical stages involved in the life cycle of a certain product. This methodology has established itself as a crucial tool for assessing and contrasting the environmental impacts of diverse agricultural systems. One prominent area of study within Life Cycle Assessment (LCA) revolves around comparing organic and conventional farming practices.

In various industries, including agriculture, experts involved in Life Cycle Assessment (LCA) have increasingly recognized the importance of considering not only environmental factors but also economic and social aspects. One commonly utilized economic approach that complements LCA is Life Cycle Costing (LCC). While the fundamental principles of LCC are still being debated and specific databases for LCC are not yet available, researchers occasionally find themselves adapting their methods within the framework of LCA to maintain consistency in terms of the functional unit and system boundary. Despite this challenge, there is limited existing literature that explores the integration of economic considerations with agricultural production in LCA.

Tomato (Solanum lycopersicum) is a popular crop worldwide and belongs to the nightshade family, Solanaceae. Tomatoes are rich in essential nutrients like vitamins A, C, and K, as well as lycopene, an antioxidant associated with various health benefits. Tomatoes thrive in areas with warm temperatures, ideally between 70–85°F (21–29°C) during the day and above 50°F (10°C) at night. They require well-drained soil with good fertility. Sandy loam and loamy soils with a pH range of 6.0–7.0 are suitable for tomato cultivation. Although tomato holds the position of being the second most economically valuable crop and the most economically valuable fruit, its economic importance is often overshadowed by the challenges associated with its cultivation. Notably, farmers face challenges ranging from variability due to factors such as local climate, soil quality, agricultural practices, and numerous interconnected elements.
Ntinas et al. 25 have highlighted the importance of electricity usage for irrigation as another influential factor. Moreover, Hasler et al 26 have also emphasized the significance of fertilizer production and use in relation to the environmental evaluation of the cultivation stage.

In their study, Williams et al 27 conducted a Life Cycle Assessment (LCA) comparing the cultivation of various crops, including wheat, oilseed rape, potatoes, and fresh market tomatoes, in both organic and conventional systems. The results revealed interesting findings regarding greenhouse gas (GHG) emissions. Specifically, they observed that the organic system had 27% lower GHG emissions per unit of product compared to the conventional system across the analyzed crops. However, when focusing specifically on greenhouse-grown tomatoes, the organic system exhibited 30% higher emissions per unit of product compared to the conventional system. This disparity was primarily attributed to lower yields associated with the organic cultivation method. In a study conducted by He et al 22 compared the Life Cycle Assessment (LCA) of greenhouse tomato production in China's organic and traditional systems. The study found that the organic system exhibited a significant 54.87% lower environmental impact compared to the traditional system. This reduction was primarily attributed to the potential decrease in the use of synthetic fertilizers and pesticides. In the past, several studies have been carried out to assess the environmental impact of the crop. These studies have been conducted in various locations, including Spain 28,29, Canada 30, Italy 31, southern and central Europe 32, and Australia 33.

A thorough review of the existing literature indicates that the comparison between organic and conventional tomato cultivation encompasses a wide range of agricultural practices, each of which deserves individual attention and emphasis. Moreover, it is noteworthy that most studies have predominantly focused on European countries, where farm sizes are typically larger, and technological advancements are more prevalent. Furthermore, previous research on tomato production systems has primarily examined the overall environmental impact of the entire production process, without delving into specific field operations. Consequently, the present study aims to address this gap by specifically focusing on the field agricultural practices within organic and conventional tomato systems. The objective is to identify the practices that contribute the most to environmental impacts and explore opportunities for optimization. Additionally, this study integrates the Life Cycle Costing (LCC) analysis to evaluate the economic aspects of agricultural practices and the overall system. By combining these dimensions, a comprehensive assessment of both the environmental and economic factors can be achieved.

Based on the above, the objectives of this study are:

- To conduct a comprehensive and simultaneous analysis of the ecological as well as the economic impacts associated with two different tomato cultivation systems (organic and conventional) throughout their growing life cycle.
- To identify specific hotspots within each system that have significant ecological and economic aspects in order to explore potential opportunities for optimizing tomato agricultural practices.

2. Materials and methods

2.1. Study area

The study conducted its analysis by gathering data from tomato farms located within the Jalandhar district of the Punjab province in India. Extensive prior research has consistently highlighted the suitability of this region for tomato cultivation 34. The favorable combination of climate and soil conditions in these areas contributes to the production of healthy tomatoes during a specific period in the autumn season while minimizing the risk of infections. For the survey conducted during the 2022-23 crop season, a careful selection was made, including a total of forty medium/small-sized tomato farms. The selection of farms was evenly divided, with twenty farms representing conventional cultivation methods and the remaining twenty farms representing organic cultivation methods. To uphold ethical practices and privacy, we have diligently obtained consent from tomato farmers in the chosen region, enabling us to gather valuable information and conduct essential experiments. Additionally, farms of similar sizes (less than 5 hectares) whose employing identical agricultural practices were chosen for the current study.

2.2. Life cycle Assessment

The life cycle assessment has been employed to quantify the environmental burdens of the analyzed systems. Figure 3 depicts the methodological flowchart employed in the study, while the subsequent sections offer a comprehensive explanation of the methodology step by step. The tests, calculations, and analysis of the results adhered to the guidelines set forth by ISO 14040 35 and ISO 14044 36 for comprehensive environmental assessments.

2.2.1. Goal and Scope of the Study

This study aims to compare the environmental effects of conventional and organic tomato farming in the northern plains of India while identifying key areas of concern. The primary objective is to determine whether cultivating one hectare of organic tomatoes has a lesser environmental impact compared to conventional methods. Furthermore, the study will analyze the economic aspects of both systems to gain insights into their financial implications. The findings from this study can be utilized to promote eco-friendly practices in tomato cultivation and inform government policies. It is worth mentioning that the cultivation of tomatoes shares similarities with eggplant, melons, and cucumber in terms of processes and mechanization. Therefore, the results of this research may also shed light on the environmental impacts of these related crops. Additionally, there is an increasing demand from consumers and governments for comprehensive information about the environmental consequences of agricultural practices, along with a push to adopt sustainable approaches in both food production and consumption.

2.2.2. Functional Unit
The study employed one hectare of tomato production as a functional unit to examine the potential environmental impacts of tomato production, specifically investigating two crucial cropping systems: conventional and organic. Scientific literature highlights that farmlands not only hold significance for agricultural production but also have a substantial environmental impact at a regional scale, particularly concerning area-based emissions. This underscores the importance of studying the environmental implications of agricultural practices beyond their immediate agricultural productivity.

### 2.2.3. System Boundaries

The current study adopts a comprehensive approach, known as a cradle-to-farm gate boundary system, which encompasses all activities from land preparation to harvesting. This means that every step involved in the process, as depicted in Fig. 4, has been taken into account. The study thoroughly examined every step involved in tomato production, including both the organic system and the conventional system. It analyzed the entire process starting from soil preparation for transplanting beds all the way to harvesting the fruits when they reached 85% maturity. Additionally, the study considered all the inputs required for each agricultural operation.

### 2.2.4. Life Cycle Inventory

The life cycle inventory (LCI) constitutes a crucial component of this study, as it serves as the foundation for subsequent processes. This phase involves the collection of data, identification of interconnections, and quantification of inputs and outputs within the system under evaluation. The LCI provides essential information for further analysis and evaluation throughout the study. Table 1 presents the average utilization of inputs and materials in both cultivation systems.

For tomato plantation, the field preparation involves thoroughly pulverizing and leveling the soil. To achieve a fine tilth, the land is plowed multiple times (around 4–5 times), followed by planking to ensure soil leveling. In organic cultivation, an additional step is taken during the last plowing, where well-decomposed cow dung is applied to the soil. As part of the life cycle assessment (LCA), inputs such as diesel used in agricultural machinery during field preparation have been documented. In the case of tomato cultivation in northern states for the autumn crop, sowing typically takes place in July-August, followed by transplantation in August-September. It was observed that an average seed rate of 250 grams was used for preparing seedlings for sowing on one hectare of land. During the fertilizer application, the following quantities were applied per hectare: Urea at 100 kg/ha, Single Super Phosphate at 100 kg/ha, and MOP (Muriate of Potash) at 115 kg/ha. In contrast, in the organic field, an average of 20 tons per hectare of solid cattle manure was utilized. This organic fertilizer was transported from nearby dairy farms using a tractor and trailer. The transfer of manure from the source to each tomato field had a mean distance of 25 kilometers. Similarly, in conventional cultivation, the mean distance for the transportation of fertilizers and pesticides from the point of procurement to the farm was recorded as 20 kilometers. All the data collected for these distances were based on the mean values obtained from the farmers participating in the study.

In conventional cultivation, crop protection was primarily achieved through the use of synthetic herbicides and fungicides. However, in organic cultivation, sour buttermilk was employed as a pesticide. The study recorded all the materials and inputs used for the life cycle analysis, including the quantity of pesticides, energy consumption, and water usage during spraying. Regarding irrigation, the water requirements for tomatoes differ based on the cultivation method. Conventional cultivation typically involves three irrigation cycles, while organic cultivation necessitates more irrigation due to the longer duration of the crop. All farmers used electricity to operate their water pumps, and the study took into account the average electricity consumption across the selected farms. The average yield of both cultivation systems was documented, revealing a disparity of approximately 37 percent (24 tons for conventional and 15 tons for organic). The reduced yields in organic cultivation can be attributed to the lower utilization of external inputs and the increased presence of pests and weeds, as indicated by Ronga et al. The necessary data that was unavailable was obtained from the widely recognized Ecoinvent version 3.7 database, which is accessible through SimaPro software. For the sake of simplicity, this study did not incorporate the environmental impacts of producing farm-used capital goods, such as farm facilities and equipment depreciation. This decision was based on previous research, which indicated that the long lifespan of such goods does not significantly impact a single production. The direct emissions resulting from fertilizer usage have been estimated based on data from previous studies, as indicated in Table 2. However, it should be noted that due to limited data availability regarding the proportion of eroded soil, the release of phosphates into surface waters through erosion was not included in the calculations.
Table 1

<table>
<thead>
<tr>
<th>Farming Practices</th>
<th>Activity</th>
<th>Conventional</th>
<th>Organic</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field preparation</td>
<td>Transformation from agriculture</td>
<td>1</td>
<td>1</td>
<td>ha</td>
</tr>
<tr>
<td></td>
<td>Transformation to agriculture</td>
<td>1</td>
<td>1</td>
<td>ha</td>
</tr>
<tr>
<td>Ploughing</td>
<td>1</td>
<td>1</td>
<td></td>
<td>times/hectare</td>
</tr>
<tr>
<td>Rototilling</td>
<td>1</td>
<td>1</td>
<td></td>
<td>times/hectare</td>
</tr>
<tr>
<td>Diesel</td>
<td>19.5</td>
<td>19.5</td>
<td></td>
<td>Liter</td>
</tr>
<tr>
<td>Transplanting</td>
<td>Seeds</td>
<td>3</td>
<td>3</td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td>Transportation from market</td>
<td>20</td>
<td>20</td>
<td>Km</td>
</tr>
<tr>
<td>Fertilization</td>
<td>Urea</td>
<td>100</td>
<td></td>
<td>Kg</td>
</tr>
<tr>
<td></td>
<td>Potassium</td>
<td>115</td>
<td></td>
<td>Kg</td>
</tr>
<tr>
<td></td>
<td>Potash</td>
<td>100</td>
<td></td>
<td>Kg</td>
</tr>
<tr>
<td></td>
<td>Organic Manure</td>
<td>-</td>
<td>20000</td>
<td>Kg</td>
</tr>
<tr>
<td>Crop Protection</td>
<td>Mancozeb</td>
<td>4.5</td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td>benimidazole</td>
<td>0.009</td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td>Chlortrifos</td>
<td>2.5</td>
<td></td>
<td>kg</td>
</tr>
<tr>
<td></td>
<td>Sour Buttermilk</td>
<td>12.5</td>
<td></td>
<td>Liter</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>1</td>
<td></td>
<td>m3</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Water</td>
<td>440.2</td>
<td>560.2</td>
<td>m3</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>65.15</td>
<td>80.15</td>
<td>kWh</td>
</tr>
<tr>
<td>Output</td>
<td>Yield</td>
<td>28</td>
<td>15</td>
<td>tonnes/hactare</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Output</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ emissions</td>
<td>3% total N applied ¹¹</td>
</tr>
<tr>
<td>N₂O emissions</td>
<td>1.25% total N applied ¹¹</td>
</tr>
<tr>
<td>NOₓ emissions</td>
<td>10% total N₂O emissions ¹²</td>
</tr>
</tbody>
</table>

2.2.5. Life cycle impact assessment

To evaluate the environmental connections between inputs and outputs in the LCA research and estimate their impact, the study utilized SimaPro version 8.1.0 software. This software, in conjunction with the Ecoinvent database, facilitated the analysis and prediction of the environmental implications based on the collected data. The assessment of emissions was conducted using the ReCiPe methodology, which includes midpoint and endpoint indicators. The endpoint indicators assess the impact on the environment across three higher aggregation levels: human health, biodiversity and ecosystem, and resource scarcity ⁴³. By utilizing these two distinct perspectives, the results were examined comprehensively to provide a more complete understanding of the environmental impacts associated with conventional and organic tomato cultivation. This approach allows for a robust analysis of the potential effects across various environmental indicators, providing a more comprehensive and reliable assessment of the cultivation systems.

3. Result and discussion

The primary objective of this study was to determine the key factors that could significantly impact the life cycle assessment (LCA) results of both systems of cultivation i.e., conventional and organic tomato cultivation. The aim was to establish connections between various agricultural practices that have a lesser detrimental effect, in order to better understand the overall environmental impacts of different cultivation systems. It is vital to examine the specific impact of each agricultural activity on the overall life cycle impacts of both cultivation systems.

3.1. Interpretation of Midpoint Characterization Results w.r.t Agricultural Practices

In Figs. 5 and 6, the variation in the results and environmental effects of tomato cultivation are illustrated through the ReCiPe Midpoint characterization. The graphs provide a distinct view of the outcomes for each cultivation system. The graphical representation demonstrates that specific farming practices, including fertilization, irrigation, transplanting, and field preparation, have notable environmental impacts. Firstly, it is evident that the fertilization and
transplanting stages exhibit a greater influence compared to other phases. This observation aligns with existing historical data that emphasizes the significant contribution of the fertilization phase in similar agricultural processes. In conventional tomato cultivation, the fertilization phase stands out as the key contributor to the overall impact, largely attributed to the production and transportation of fertilizers, which heavily depend on fossil fuels. This aligns with the findings of previous studies, indicating that conventional farming practices prioritize maximizing yield in economically viable ways, with some consideration given to environmental factors. The environmental impact of irrigation is primarily negative, mainly because of its excessive freshwater usage for crop hydration and its reliance on coal-based electricity, which intensifies resource consumption. However, in comparison to other practices, irrigation's contribution is relatively limited since it relies less on inputs from nature and technology. Nevertheless, the remaining cultivation practices also exert a substantial impact due to the utilization of resources and inputs.

In the realm of organic tomato cultivation, it has been determined that the field preparation and transplantation stages exert a more substantial influence compared to other practices such as organic fertilization, crop management, and irrigation. Furthermore, an intriguing observation emerged, indicating that irrigation practices in organic cultivation possess an approximately 18.85% greater impact compared to conventional cultivation. This discrepancy primarily arises due to the prolonged lifespan of organic crops, which necessitates higher water consumption when contrasted with conventional crops. Consequently, escalated water usage contributes to the heightened environmental repercussions associated with irrigation in organic cultivation.

### 3.2. Interpretation of Midpoint Characterization Results w.r.t impact categories

In terms of global warming potential (GWP), the organic cultivation method demonstrated a significantly lower impact, with a reduction of approximately 40% compared to the conventional system. The conventional system exhibited a GWP of 1307.917 kg CO$_2$ eq per hectare, while the organic system recorded 904.708 kg CO$_2$ eq per hectare. When considering the contribution of individual stages in the management process, the application of fertilizer had the highest impact in the conventional system, accounting for approximately 44% of the total. Other stages such as transplantation, field preparation, irrigation, and crop protection contributed 30.63%, 15.80%, 7.17%, and 2.22% respectively. It is evident that higher nitrogen and phosphorus usage contributes to increased greenhouse gas emissions. The earlier research also provides substantial evidence supporting the relationship between greenhouse gas emissions and the amount of synthetic nutrients used in crop production. However, in the context of organic farming, field preparations were found to have the highest impact, accounting for 44.28% of the total. This was followed by field emission activities at 23.84%, irrigation at 12.76%, organic fertilizer at 11.36%, and crop protection at 7%—the stage with the lowest impact within the GWP category. This notable decrease in the impact of fertilizers compared to the conventional system is consistent with the research conducted by Ronga et al which highlighted the lower contribution of organic cultivation to the GWP impact category when compared to conventional tomato production. According to Longo et al a significant amount of the influence on the natural ecosystem is attributable to the use of fertilizers, insecticides, and fuel by agricultural machinery.

Based on the data provided in Table 3, it is evident that, besides the Global Warming Potential (GWP), other impact indicators including terrestrial ecotoxicity, human toxicity, and fossil resource scarcity pose substantial concerns. Notably, the fertilization phase stands out as the major contributor, responsible for over 40 to 60 percent of the impact in each category. This significant influence can be attributed to the production, transportation, and application of fertilizers during this particular phase. The extensive use of synthetic fertilizers significantly increased the ecotoxicity of the ecosystem which led to an increase above impact categories.

Conversely, in organic cultivation, the transplanting of tomato plants assumes a significant role in terms of impact. This can be attributed to the transportation and utilization of resources and materials preceding the transplanting phase. Notably, the shift to organic cultivation demonstrates an average reduction of 35 percent across all categories, except for Marine Eutrophication and Land use. The amplified contribution to marine eutrophication...
### Interpretation of Endpoint Results

Figure 7 and Fig. 8 illustrate the variation in the results of tomato cultivation based on the ReCiPe Endpoint score. These figures visually represent the diverse outcomes and effects observed in different environmental categories as a result of tomato cultivation. The final results obtained from aggregating the individual impacts of various agricultural practices in conventional tomato cultivation are presented in Table 4. The combined score represents a single-point assessment, with a total impact of 80.04 points. Among the different categories, Human health has the highest score, accounting for 71.94 points and thus holding a dominant position. Fertilization and irrigation practices stand out prominently, with scores of 31.08 points and 24.47 points, respectively.

### Table 3

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Total</th>
<th>%change</th>
<th>Field Preparation</th>
<th>Transplanting</th>
<th>Fertilization</th>
<th>Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv</td>
<td>Org</td>
<td>Conv</td>
<td>Org</td>
<td>Conv</td>
<td>Org</td>
<td>Conv</td>
<td>Org</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>1307.917</td>
<td>904.708</td>
<td>30.83</td>
<td>206.715</td>
<td>215.754</td>
<td>400.646</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>8.19E-04</td>
<td>5.36E-04</td>
<td>34.57</td>
<td>1.08E-04</td>
<td>1.23E-04</td>
<td>1.41E-05</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>35.493</td>
<td>14.281</td>
<td>59.76</td>
<td>4.576</td>
<td>5.276</td>
<td>2.362</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>3.530</td>
<td>2.894</td>
<td>18.01</td>
<td>1.850</td>
<td>1.882</td>
<td>0.125</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>2.507</td>
<td>1.237</td>
<td>50.66</td>
<td>0.599</td>
<td>0.625</td>
<td>0.068</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
<td>3.595</td>
<td>2.947</td>
<td>18.01</td>
<td>1.880</td>
<td>1.914</td>
<td>0.128</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>5.583</td>
<td>2.290</td>
<td>58.98</td>
<td>1.041</td>
<td>1.117</td>
<td>0.123</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>0.397</td>
<td>0.135</td>
<td>65.93</td>
<td>0.035</td>
<td>0.036</td>
<td>0.012</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>0.034</td>
<td>0.066</td>
<td>-96.81</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Terrestrial toxicity</td>
<td>kg 1,4-DCB</td>
<td>4541.529</td>
<td>2064.485</td>
<td>54.54</td>
<td>538.377</td>
<td>550.440</td>
<td>151.325</td>
</tr>
<tr>
<td>Freshwater toxicity</td>
<td>kg 1,4-DCB</td>
<td>40.720</td>
<td>11.983</td>
<td>70.57</td>
<td>3.416</td>
<td>3.499</td>
<td>1.112</td>
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<tr>
<td>Marine toxicity</td>
<td>kg 1,4-DCB</td>
<td>58.759</td>
<td>16.939</td>
<td>71.17</td>
<td>4.928</td>
<td>5.074</td>
<td>1.520</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>33.609</td>
<td>19.215</td>
<td>42.83</td>
<td>7.556</td>
<td>7.746</td>
<td>1.480</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>1456.337</td>
<td>402.888</td>
<td>72.34</td>
<td>202.995</td>
<td>205.560</td>
<td>21.433</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>117.174</td>
<td>135.343</td>
<td>-15.51</td>
<td>6.103</td>
<td>6.211</td>
<td>89.072</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>11.255</td>
<td>2.193</td>
<td>80.51</td>
<td>1.515</td>
<td>1.530</td>
<td>0.094</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>435.554</td>
<td>284.566</td>
<td>34.67</td>
<td>64.192</td>
<td>84.755</td>
<td>109.361</td>
</tr>
<tr>
<td>Water consumption</td>
<td>m3</td>
<td>475.770</td>
<td>572.077</td>
<td>-20.24</td>
<td>0.594</td>
<td>0.694</td>
<td>9.321</td>
</tr>
</tbody>
</table>

is primarily attributed to the elevated water consumption and electricity usage involved in pumping water from ground level\(^{54,55}\).

### 3.3. Interpretation of Endpoint Results

The results obtained from aggregating the individual impacts of various agricultural practices in conventional tomato cultivation are presented in Table 4. The combined score represents a single-point assessment, with a total impact of 80.04 points. Among the different categories, Human health has the highest score, accounting for 71.94 points and thus holding a dominant position. Fertilization and irrigation practices stand out prominently, with scores of 31.08 points and 24.47 points, respectively.
Furthermore, within the score of 31.08 points for fertilization, a significant contribution of 92.38% is attributed to the Human health category. Similarly, within the 24.47 points scored for irrigation, 85.43% of the contribution comes from indicators related to Human health.

In contrast, organic cultivation yields a total score of 58.30 points, which is approximately 27.16% lower than conventional cultivation. Notably, the irrigation phase exhibits the highest point contribution, amounting to 30.90 points, making a 26.28% increase compared to the conventional phase. The scores for field preparation and transplanting remain unchanged, while there is a significant 87.54% reduction in the total score for the fertilization phase (31.08 points for conventional and 3.87 points for organic). Additionally, the score for the crop protection phase experiences a one-third reduction (4.53 points for conventional and 3.0 points for organic) as a result of the shift from synthetic pesticide spray in conventional cultivation to organic spray in organic cultivation. These findings indicate that organic cultivation substantially diminishes the significance of the fertilization phase, while irrigation becomes a prominent contributing factor due to higher water consumption and the utilization of coal-based electricity.

### Table 4

<table>
<thead>
<tr>
<th>Damage category</th>
<th>Unit</th>
<th>Total</th>
<th>%age Change</th>
<th>Field Preparation</th>
<th>Transplanting</th>
<th>Fertilization</th>
<th>Irrigation</th>
<th>Crop Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conv</td>
<td>Org</td>
<td></td>
<td>Conv</td>
<td>Org</td>
<td>Conv</td>
<td>Org</td>
<td>Conv</td>
</tr>
<tr>
<td>Total</td>
<td>80.04</td>
<td>58.30</td>
<td>27.16</td>
<td>11.64</td>
<td>12.20</td>
<td>8.32</td>
<td>8.32</td>
<td>31.08</td>
</tr>
<tr>
<td>Human health</td>
<td>71.94</td>
<td>50.90</td>
<td>29.25</td>
<td>10.82</td>
<td>11.30</td>
<td>7.19</td>
<td>7.19</td>
<td>28.71</td>
</tr>
<tr>
<td>Ecosystems</td>
<td>7.27</td>
<td>6.89</td>
<td>5.18</td>
<td>0.63</td>
<td>0.66</td>
<td>1.11</td>
<td>1.11</td>
<td>1.83</td>
</tr>
<tr>
<td>Resources</td>
<td>0.83</td>
<td>0.47</td>
<td>43.38</td>
<td>0.18</td>
<td>0.25</td>
<td>0.02</td>
<td>0.02</td>
<td>0.54</td>
</tr>
</tbody>
</table>

#### 3.4. Life cycle costing

The analytical method of life cycle costing (LCC) was employed to examine the expenses linked to tomato production throughout its entire cultivation period. The LCC approach was utilized to calculate the costs involved in producing tomatoes, which encompassed various stages for both the selected cultivation systems for tomatoes. Costs were estimated based on market prices of energy sources (diesel and electricity) and materials (chemical fertilizers, herbicides, and insecticides). These prices were obtained from field surveys, reliable government websites, and published literature, focusing on the Indian market. The net economic profit was determined in terms of Indian Rupees per hectare or per unit of output by subtracting the yield price from the total production costs. Moreover, when calculating the costs of agricultural practices and revenues, the following factors were taken into consideration:

- The minimum rate of wage has been taken for the labor work of removal of weedicide manually. They generally labor more than 8 hours per day and are paid between 200 and 400 INR per day, depending on local living conditions.
- The cost of diesel per liter has been taken as an average of the selected crop season prices was 89.57 INR in both cultivation systems.
- In both systems, the cost of electricity for crop irrigation has been considered as zero due to the government of India's policy of providing free electricity to the agriculture sector.
- The fixed capital or indirect costs such as land improvements, indirect labor, and depreciation on machinery and equipment. Interest, rent, farm buildings, and work animals have not been considered in this study as the lifespan of such commodities is too long to have a significant impact on single crop production as stated in earlier studies.
- The farm gate price for conventional tomatoes has been set at Rs. 5 per kilogram. However, the price of organic tomatoes can vary depending on factors such as quality, shelf life, and proximity to the sales point. In general, organically produced tomatoes tend to have a higher price, ranging from approximately Rs. 6 to 10 per kilogram. The higher price of organic tomatoes is attributed to their premium market value and the perception of their superior nutritional quality. Since the selling price of organic tomatoes is uncertain, an estimation has been made based on the Benefit to Cost ratio.

Using current market prices of materials and energy sold in the selected regions, the production of cost of tomato was estimated to be 31914.93 INR for conventional and 26086.918 INR for organic cultivation system (Table 5). The key variable related to the production cost of tomatoes are (in the case of conventional) consist of cost of seedling (27.09%), combining cost of all pesticide/weedicides used (20.61%), combining the cost of all fertilizers used (18.09%) and cost of Labor expenses (15.04%). In the case of organic cultivation, the cost of transplanting (33.14%) and cost of labor expenses for the manually removal of weeding (28.75%) lend the major portion of total cost with a share of 33.14% and 28.75%. It can be seen that the production cost per hectare of organic is lower than that of conventional cultivation (18.26%). For further understanding, the Benefit-Cost Ratio (BCR) is calculated by dividing the Net returns of a selected cultivation system by the total cost of production.
Table 5
Costing of all the inputs with respect to both cultivation systems

<table>
<thead>
<tr>
<th>Economic Consideration</th>
<th>Cost (INR)</th>
<th>Conventional Cultivation</th>
<th>Organic Cultivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Preparation</td>
<td>Diesel Burning in Agriculture machinery</td>
<td>1747.59 (5.48)</td>
<td>1747.59 (6.70)</td>
</tr>
<tr>
<td>Transplanting</td>
<td>Seedling</td>
<td>8645 (27.09)</td>
<td>8645 (33.14)</td>
</tr>
<tr>
<td>Transportation of seed from the market</td>
<td></td>
<td>179.24 (0.56)</td>
<td>179.24 (0.69)</td>
</tr>
<tr>
<td>Labor Expenses</td>
<td></td>
<td>4800 (15.04)</td>
<td>4800 (18.40)</td>
</tr>
<tr>
<td>Fertilization</td>
<td>Phosphate fertilizer, as P2O5</td>
<td>3000 (9.40)</td>
<td>0</td>
</tr>
<tr>
<td>Potassium fertilizer, as K2O</td>
<td></td>
<td>2185 (6.85)</td>
<td>0</td>
</tr>
<tr>
<td>Urea, as N</td>
<td></td>
<td>600 (1.88)</td>
<td>0</td>
</tr>
<tr>
<td>Transportation of fertilizers/manure from market/farm</td>
<td></td>
<td>179.24 (0.56)</td>
<td>215.088 (0.82)</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Electricity</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Crop protection</td>
<td>Mancozeb</td>
<td>1800 (5.64)</td>
<td>0</td>
</tr>
<tr>
<td>Chlorphriphos + Cypermethrin</td>
<td></td>
<td>900 (2.82)</td>
<td>0</td>
</tr>
<tr>
<td>Emamectin Benzoate</td>
<td></td>
<td>1110 (3.48)</td>
<td>0</td>
</tr>
<tr>
<td>Diesel Burning in Sprayer</td>
<td></td>
<td>268.86 (0.84)</td>
<td>0</td>
</tr>
<tr>
<td>Labour Expenses for Crop Protection</td>
<td></td>
<td>2500 (7.83)</td>
<td>7500 (28.75)</td>
</tr>
<tr>
<td>Harvesting</td>
<td>Hand Picking/Transportation charges up to the Selling point</td>
<td>4000 (12.53)</td>
<td>3000 (11.50)</td>
</tr>
<tr>
<td>Total Cost</td>
<td></td>
<td>31914.93</td>
<td>26086.918</td>
</tr>
<tr>
<td>Net Sales of crop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomato Production (Ton per Hectare)</td>
<td></td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>INR/ton</td>
<td></td>
<td>5000</td>
<td>To be estimated</td>
</tr>
</tbody>
</table>

(Figure in parentheses indicate percentage to total production cost)

From the economic point of view, it is visible that in order to match the BCR ratio of 2.96 for conventional production at 5 rupees per kg, the cost of organic tomatoes needs to be fixed at 6.5 INR per kg which is 30 percent higher. When focusing on the marketing scenario, the trend of buyers does not seem highly favorable to spend more than 25 to 50 percent excess to the conventional one. To capitalize on the market potential for organic tomatoes, it is recommended to find a pricing strategy that balances the higher cost of organic production with consumer affordability. Keeping the price difference within the acceptable range of 15 to 30 percent can help attract customers who value organic products and are willing to pay a modest premium for them. Additionally, it is important to consider the marketing strategies based on the size of the farm. Small-scale farms, with limited quantities available, can focus on localized marketing efforts such as word-of-mouth within the local community. However, larger farms with higher production volumes should explore additional marketing channels beyond roadside vendors and word-of-mouth. Allocating a marketing budget for activities like advertisements and expanding sales to other cities can enhance market reach and increase the potential customer base for organic tomatoes. This increases the potential for reaching a wider customer base and commanding better prices, resulting in a higher BCR ratio.

In conclusion, to promote organic tomato production and make it economically viable, it is important to consider pricing strategies that maintain a reasonable price differential compared to conventional tomatoes. Additionally, supporting small-scale farmers with localized marketing efforts and providing larger-scale farmers with resources for wider market reach can improve the overall BCR ratio. Government intervention through registration, subsidiaries, and support programs can play a crucial role in supporting and incentivizing organic farming practices.

4. Conclusions

A comparative analysis was conducted in the present study to assess the cultivation systems of tomatoes (conventional and organic) in Northern India. The research focused on evaluating the disparities between the two systems in terms of their impact on ReCiPe Midpoint and Endpoint impact categories. The findings of the study confirm that in conventional tomato cultivation, fertilization activity has the most significant impact on the overall assessment. This is mainly due to the production and transportation of fertilizers, which heavily rely on fossil fuels. Moreover, the transplanting process also contributes to the environmental impact due to its heavy reliance on diesel fuel consumption. On the other hand, in organic cultivation, the impact of fertilization is reduced to 86.16 percent on average across all midpoint impact categories. Switching to organic cultivation led to notable reductions in impact categories such as mineral resource scarcity, human non-carcinogenic toxicity, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, and global warming potential. This implies that organic farming practices, which utilize alternative and less resource-intensive fertilization methods, help mitigate the environmental impact.
associated with conventional fertilization practices. According to the endpoint approach, organic cultivation exhibits a notable reduction, with a total score of 58.30 points, which is approximately 27.16% lower than the 80.04 points obtained in conventional cultivation. With regard to the various categories, Human health surpasses others with the highest score, establishing its dominant position in the assessment. Specifically, in conventional cultivation, Human health attains a score of 71.94 points, while in the case of organic cultivation, it achieves a slightly lower score of 50.94 points. The findings of the study suggest that reducing fertilizer usage and embracing renewable energy are crucial factors in minimizing the impact categories being evaluated. Moreover, in order to evaluate the financial viability, a Life Cycle Cost (LCC) analysis was conducted, which involved interviews with farmers and agriculture input sellers. The analysis indicated an increase in production costs by approximately 20 percent compared to the organic system. The primary factor contributing to higher production costs in conventional cultivation was the cost of fertilizer and pesticide usage, which accounted for around 38 percent of the total. To improve the financial viability of conventional cultivation, it would be beneficial to explore strategies that reduce the reliance on expensive fertilizers and pesticides. Implementing sustainable agricultural practices, such as integrated pest management, organic fertilizers, and crop rotation, can help reduce the cost of inputs while maintaining productivity.

The overall Life Cycle Assessment (LCA) provides a clear depiction of the environmental hotspots associated with various agricultural practices, underscoring the necessity for implementing more sustainable techniques in tomato cultivation. With fertilization being the primary contributor to environmental impact categories, exploring strategies to enhance fertilizer efficiency becomes crucial to minimize waste and mitigate environmental consequences.

To safeguard the environment, it is recommended to impose restrictions on the use of fertilizers and pesticides, setting thresholds to prevent excessive application. Moreover, the study highlights the importance of effective policy formulation at the government level. Policies that facilitate affordable access to solar energy equipment for farmers can make alternative practices more financially viable and enhance the overall sustainability of the maize production cycle, which is crucial for the global economy.

**Declarations**

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**CRediT authorship contribution statement**

**Rohit Kumar:** Idea generation, Conceptualization, Investigation, Writing – original draft, Visualization.

**Arvind Bhardwaj:** Supervision, Writing-review & editing, Conceptualization, Validation of the final paper.

**Lakhwinder Pal Singh:** Supervision, review & editing, Visualization, Investigation.

**Gurraj Singh:** Data, LCA analysis, and Co-writing of the first draft of the manuscript

**Anupam Kumar:** Visualization, contributed to the concept, and editing of the article.

**Kanhu Charan Pattayak:** Funding acquisition, Conceptualization, Co-writing of the conception and Design, and language assistance

All authors have read and agreed to the published version of the manuscript.

**Data availability Statement:**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**References**


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Figure 1

Typical Life cycle assessment of a product

Figure 2

A typical life cycle of a tomato, depicting the sequential stages from seed to tomato.
Figure 3

Methodological flowchart of LCA

Figure 4

The system boundaries for open-field tomato cultivation encompass the included processes.
Figure 5

Characterization value of conventional tomato production based on the ReCiPe Midpoint method.
Figure 6

Characterization value of organic tomato production based on the ReCiPe Midpoint method.
Figure 7

Endpoint score results with respect to conventional cultivation of tomato.
Figure 8

Endpoint score results with respect to organic cultivation of tomato.