Estimation of carbon emission from production of potato in subtropics of jammu

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Abstract: Potato cultivation plays a vital role in food security and rural livelihoods, particularly in the subtropical regions of India where it is grown intensively. However, the environmental impact of its production, especially in terms of carbon emissions, remains underexplored. The present study was conducted in the subtropical region of Jammu, Union Territory of Jammu and Kashmir, covering four villages—Makhanpur, Lasswadi, Tarachak, and Kotli Mian Fateh in the Bishnah block of Jammu district to assess the carbon emissions associated with potato cultivation. The required data were collected from 100 potato growers using a structured, interview-based questionnaire covering various input categories. The results indicated that transportation activities were the largest source of emissions, contributing 594.56 kg CO_2e, followed by plantation and land preparation operations, contributing 400.63 kg CO_2e and 400.03 kg CO_2e, respectively (each 23.5%). Among input categories, machinery use including tractors, implements, and tools contributed the highest emissions at 858.92 kg CO_2e, accounting for 50.15% of the total. In contrast, emissions from human labour were minimal, contributing only 6.76% of the total emissions. The findings underscore the significant role of mechanized operations in the carbon footprint of potato farming and highlight the need for adopting energy-efficient practices. This study offers novel insights into emission profiling of potato cultivation in subtropical agro-climatic conditions and provides a practical framework for promoting low-carbon agricultural practices in the region.

Keywords: carbon emissions, potato cultivation, energy use, emission factors, subtropical agriculture

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1 Introduction

Potato (*Solanum tuberosum*) is one of the world's most important food crops and has been designated as the "Food for the Future" by the Food and Agriculture Organization (FAO) due to its adaptability, high yield potential, short growing cycle, and nutritional richness (Khar and Zaffar, 2023). Globally, it is cultivated over 18 million hectares, with an annual production of approximately 373.5 million tonnes and a productivity of 20.75 tonnes per hectare (FAO, 2023). In India, potato production reached 56.1 million tonnes in 2022 from an area of 2.22 million hectares with a productivity of 25.27 t ha^{-1} (DES, 2023). In the Union Territory of Jammu and Kashmir, production has grown by over 83% over the past five decades, with a total output of 0.036 million metric tonnes in 2020–21 (DES, 2023).

This growth, however, has been accompanied by

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a rise in energy-intensive practices involving fossil fuels, mechanization, synthetic fertilizers, and chemicals. The increasing reliance on such inputs has led to a significant surge in carbon emissions from agriculture, contributing to global climate change (Lal, 2004; Sah and Devakumar, 2018). With the global population projected 9.2 billion in 2050 (Zaffar et al., 2023) and continue to peak at 10.3 billion by the mid-2080s (UNDESA, 2024; Zaffar et al., 2025), the challenge of producing more food while reducing environmental impacts is more pressing than ever. In this context, understanding the carbon footprint of individual crops, such as potato, is essential for developing sustainable agricultural strategies.

In this regard various studies have attempted to quantify the carbon emissions associated with potato production in different regions. Singh (2022) measured greenhouse gas (GHG) emissions from potato fields in Himachal Pradesh using closed-chamber methods and found fertilizer management to be a key emission driver. Kumar et al. (2023) applied life cycle assessment (LCA) to compare organic and conventional potato systems in Northern India, identifying fertilization as the dominant source of emissions. Similarly, Bharadwaj (2023) analyzed energy use and carbon footprint in rainfed versus irrigated systems, emphasizing the role of mechanization and irrigation. Pathak et al. (2014) showed that fertilizer use, irrigation, and residue burning were major contributors to agricultural GHG emissions in India and emphasized the need for crop-specific interventions. While existing studies have significantly contributed to our understanding of carbon emissions in potato production, they often emphasize either broad regional assessments or controlled experimental conditions. However, such approaches may not fully capture the on-ground variability in energy use and emission profiles that exist across smallholder, resource-constrained farming systems like those in subtropical Jammu. In regions with fragmented landholdings, variable input availability, and inconsistent access to mechanization, emission patterns can differ substantially even within short geographic distances (Singh, 2022; Alam et al., 2005).Thus, the present study addresses these gaps by employing primary data collection from farmers to estimate and compare emissions from each major activity and input category. The findings offer region-specific insights necessary for formulating low-carbon, input-efficient strategies that are both environmentally and economically sustainable with following objectives:

(1) To estimate operation and input-wise carbon emissions from potato cultivation in subtropical Jammu.

(2) To assess the contribution of different energy sources and farm activities to total emissions.

(3)To analyze the relationship between energy input and carbon emissions for identifying mitigation strategies.

2 Materials and methods

2.1 Locale of the study

The study was conducted in four villages namely Makhanpur, Lasswadi, Tarachak, and Kotli Mian Fateh located in the Bishnah block of Jammu district at 32°61′ N latitude and 74°86′ E longitude (Figure 1). The region represents the sub-mountainous, undulating agro-climatic conditions of the Union Territory of Jammu and Kashmir (Figure 1).

2.2 Experimental design and statistical analysis

The study followed a Completely Randomized Design (CRD), with 100 potato farmers from four villages Makhanpur, Lasswadi, Tarachak, and Kotli Mian Fateh serving as experimental units. In each village 25 farmers were selected randomly for data collection during the 2022–23 cropping season, corresponding to the winter potato cycle, which is predominantly cultivated in the subtropical plains of Jammu, especially in the Bishnah and R.S. Pura blocks (CDAP, 2014). These areas are recognized as the key potato-growing zones of the Jammu division due to favorable agro-climatic conditions and extensive farmer participation in potato cultivation.

For this study, Bishnah block was purposefully chosen as the study location owing to its large area under potato cultivation and the high concentration of smallholder farmers actively engaged in winter potato farming. Within the block, the four villages were randomly selected to ensure unbiased representation across varied farm practices and conditions, thereby enhancing the reliability and robustness of the study findings.

The data were collected on key inputs (seed, fertilizers, pesticides, irrigation, diesel, electricity, labor, machinery use) and output (yield), and used to calculate operation-wise carbon emissions under a Tier I system boundary using standard emission factors.

For comparative analysis, one-way Analysis of Variance (ANOVA) was used to determine significant differences in operation-wise carbon emissions among the four villages. The statistical analysis was conducted using SPSS Statistics Version 16.0, with significance level set at $p \leq 0.05$.

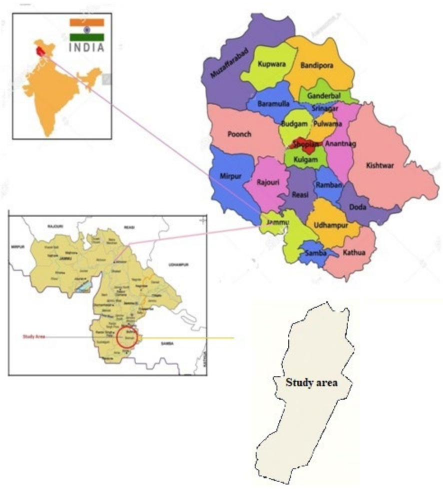


Figure 1 Map of the study area

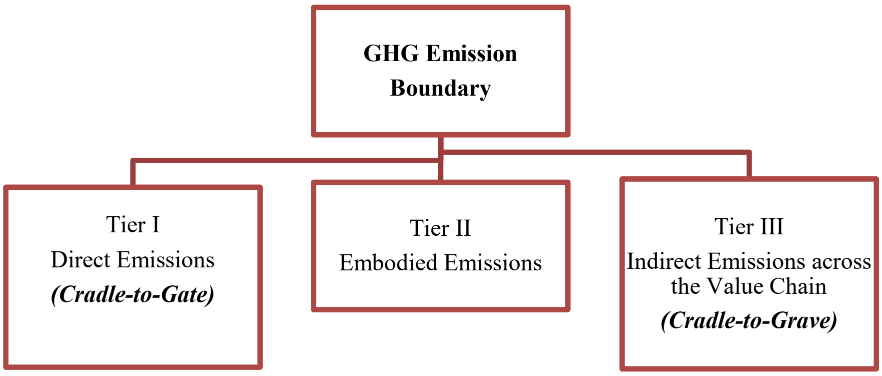


Figure 2 Various greenhouse gas emission boundaries

2.3 Carbon footprint estimation

The carbon footprint was estimated by calculating the amount of greenhouse gases (GHGs) emitted throughout the product's life cycle. Before conducting the estimation, three key components were considered:

(1) Selection of greenhouse gases (GHGs);

(2) Boundary setting;

(3) Data collection.

2.3.1 Selection of Greenhouse Gases (GHGs)

The choice of GHG estimation methods depends on the nature of the activity for which the carbon footprint is being assessed (Pandey et al., 2011). Typically, the estimation includes emissions of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), as the significance of each gas varies across agricultural activities (e.g., CH_4 is more relevant in cattle farming). However, several studies have focused solely on CO_2 emissions when calculating carbon footprints (Bayssi et al., 2024; Craeynest and Streatfeild, 2008). In the present study, the carbon footprint was estimated based exclusively on CO_2 emissions, expressed in units of carbon dioxide equivalent (CO_2e) (Muthu, 2015).

2.3.2 Setting the boundary

The boundary refers to a conceptual line that defines the activities included in the carbon footprint calculation, specifying the scope within which emissions are measured. In general, carbon foot printing is conducted using one of three established boundary settings (Figures 2 and 3).

Tier I: Direct Emissions

This includes GHG emissions from sources owned or controlled by the farmer, typically involving on-site fuel combustion, such as diesel used in tractors or generators (Teske et al., 2022).

Tier II: Embodied emissions

This refers to indirect emissions from purchased energy (e.g., electricity) and the production of farm inputs like fertilizers, pesticides, and equipment, covering both on-farm and off-farm input manufacturing (Teske et al., 2022).

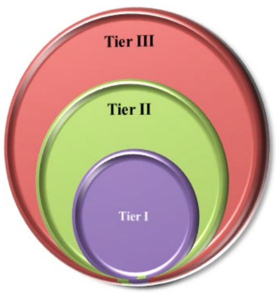


Figure 3 Selection of tier for estimation carbon emission

Tier III: Indirect emissions across the value chain

The broadest boundary encompasses all indirect emissions throughout the product life cycle, including production, distribution, consumption, and disposal stages (Teske et al., 2022).

In the present study, the Tier I boundary was selected to focus on emissions generated directly on the farm by the farmers themselves. This boundary was considered appropriate due to its practical applicability and ease of data collection, particularly in smallholder farming systems, such as those in the subtropical region of Jammu, where detailed records for upstream or life-cycle processes are generally lacking. Moreover, adopting the Tier I approach allows for a focused assessment aimed at developing targeted, farm-level mitigation strategies, including improved fuel efficiency, optimized input use, and reduced emissions from machinery operations.

2.3.3 Data collection

The data on various inputs including seed, fertilizers, chemicals, irrigation, human and animal labor (i.e., direct inputs under Tier I)—as well as output in the form of crop yield, were collected using a pre-tested performa. A combination of the recall method and direct field measurements was employed for data collection from farmers in the selected villages. The collected data were then converted into corresponding carbon emissions by multiplying the input quantities with their respective carbon emission coefficients (Sah and Devakumar, 2018). The triangulation approach was used for accuracy and reliability of farmer-reported data in which Input data were cross-verified with field observations during site visits, including checks on actual fuel usage, machinery operations, and visible input stocks. Additionally, responses were validated against peer responses within the same village to resolve any discrepancies. Based on the carbon emission equivalents of the inputs and output (Table 1), the total carbon emissions and emission intensity were calculated to quantify the carbon footprint of potato production in the subtropical region of Jammu.

2.4 Carbon emission estimation

The carbon footprint was estimated based on standard emission factors, which are widely used and accepted in agricultural emission assessments (Pandey et al., 2011). According to Cheng et al. (2011), the general formula applied is:

$$\text{Carbon footprint} = \text{Agriculture Input} \times E_f \quad (1)$$

The expression each input is given in the subsequent headings below.

2.4.1 Fertilizers

The emission factor varies depending on the type and quantity of fertilizer used. Carbon emissions from fertilizers were calculated using the following equation:

$$Emissions\ from\ Fertilizers\ (kg\ CO_2e) = Quantity\ (kg) \times E_f(\frac{kg\ CO^2e}{kg}) \quad (2)$$

To estimate emissions, fertilizers such as urea, DAP (Diammonium Phosphate), MOP (Muriate of Potash), and FYM (Farm Yard Manure) were first converted into their nutrient equivalents—Nitrogen (N), Phosphorus (P), Potassium (K), and Zinc (Zn)—using the following standard conversion factors (Vitosh, 1990).

$$\text{Urea} = 0.46\text{N} + 0.00\text{P} + 0.00\text{K} \quad (3)$$

$$\text{MOP} = 0.00\text{N} + 0.00\text{P} + 0.60\text{K} \quad (4)$$

$$\text{DAP} = 0.18\text{N} + 0.46\text{P} + 0.00\text{K} \quad (5)$$

$$\text{FYM} = 0.05\text{N} + 0.02\text{P} + 0.05\text{K} \quad (6)$$

Table 1 Carbon emission equivalents for the production of potato crop

Input sources	CO_2 Emission factor	Reference
Nitrogen (kg)	1.30	Lal (2004)
Phosphorus (kg)	0.20	Lal (2004)
Potassium (kg)	0.15	Lal (2004)
Diesel (liter)	2.68*	IPCC (2006)
Electricity (kWh)	0.82	Lal (2004)
Human (day)	0.86	Lal et al. (2020)
Seed (kg)	1.22	Lal et al. (2020)
Tractor (MJ)	0.71	Hosseinzadeh-Bandbafha et al. (2018)
Farm machinery (hr)	3.32	Lal et al. (2020)
Herbicide (kg)	6.3	Lal (2004)
Insecticide (kg)	5.1	Lal (2004)
Fungicide (kg)	3.9	Lal (2004)

*Diesel emission factor (2.68 kg CO_2 L^{-1}) was derived from the default net calorific value (NCV) for gas/diesel oil (43.33 TJ 10^3 t^{-1}) and the default CO_2 emission factor (74,100 kg CO_2 TJ^{-1}) as provided in IPCC.

2.4.2 Pesticides

The Pesticide use also contributes to GHG emissions. The emissions were estimated using the following equation and the emission factor for each type of chemical or pesticide used is given in the Table 1.

$$\text{Emissions from Pesticides} = \text{Quantity (kg)} \times E_f(\text{kg } CO_2e/\text{kg}) \quad (7)$$

2.4.3 Irrigation

The irrigation requirements were met through canals, rainfall, and groundwater. For groundwater irrigation, farmers used two main power sources: electric motors and diesel-powered pumps. The emissions were calculated as follows:

2.4.4 Electric motored pump

The type of irrigation determines water consumption and energy use. If powered by electricity or diesel pumps, the associated emissions can be estimated as;

$$\text{Emissions (kg } CO^2e) = \text{Electricity Used (kWh)} \times \text{Emission Factor (kg } CO_2e/\text{kWh}) \quad (8)$$

2.4.5 Diesel-powered pumps

The emission from the diesel powered can be calculated by estimating the amount of fuel used and can be determined by the following equation:

$$\text{Emissions (kg } CO^2e) = \text{Diesel Consumed (L)} \times E_f(\text{kg } CO_2e/\text{L}) \quad (9)$$

2.4.6 Machinery usage

The operations such as ploughing, sowing, and harvesting were carried out using tractor-operated machinery. The emissions from machinery use included contributions from Tractor fuel use, Machinery operation and Human labor. Each component was estimated separately using its specific emission factor (Table 1). The total emissions from machinery use were computed as the sum of all contributing components.

2.4.7 Total carbon emission

The total carbon emissions from potato production were calculated by summing the emissions from all relevant sources. This can be mathematically represented as:

$$\sum_1^n a1 + a2 + a3 + \cdots an \quad (10)$$

Where,

a_1, a_2---a_n represents the nth number of sources of emission.

2.5 Emission intensity

The emission intensity can be estimated using the following expression

$$\text{Emission Intensity}\left(\frac{\text{kg CO}^2\text{e}}{\text{ton}}\right)=\frac{\text{Total Emissions (kg CO}^2\text{e)}}{\text{Total Crop Yield (tons)}} \qquad (11)$$

3 Results and discussion

3.1 Emission of carbon (kgCO_2e) in potato production

Potato cultivation involves a series of operations throughout the crop's growth cycle, each contributing to the overall carbon footprint. The process begins with land preparation, including tillage and ridge formation, followed by planting and covering the crop. Fertilizer application is then conducted, supported by intercultural operations aimed at effective weed management. Harvesting is carried out using digging and rooting techniques, while transportation marks the final phase. Each of these operations contributes differently to carbon emissions. The Table 2 provides a comprehensive breakdown of emissions from various sources associated and total emission from each operation illustrated in Figure 5 respectively.

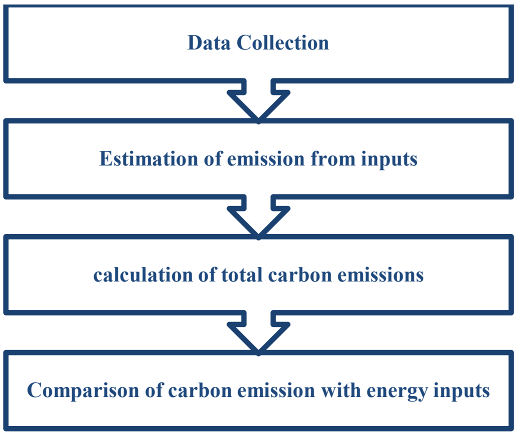


Figure 4 Methodological workflow for estimating carbon emissions from potato production

Table 2 Emission of carbon (kgCO_2e) for various operations of potato production

Operation	Tractor +Machinery (kgCO_2e)	Diesel (kgCO_2e)	Human (kgCO_2e)	Chemical/fertilizer Seed (kgCO_2e)	Electricity (kgCO_2e)	Total (kgCO_2e)
Land Preparation	282.61	116.37	1.04	-	-	400.02
Planting	25.27	13.28	19.48	345.60	-	403.63
Fertilizer application	-	-	1.075	183.39	-	184.47
Intercultural	6.23	-	8.06	-	-	14.30
Digging and Rooting	43.16	-	55.90		-	99.06
Weighing and Stitching	-	-	3.82		-	3.82
Transport	501.65	79.47	13.44		-	594.56
Irrigation		-	14.19		-	14.19
Total	**858.92**	**209.12**	**117.00**	**528.99**	**-**	**1714.03**

In the present study, transportation contributed the highest carbon emissions at 594.56 kg CO_2e, followed by planting (403.63 kg CO_2e) and land preparation (400.02 kg CO_2e). The higher emissions from transportation were primarily due to diesel-powered tractor usage, consistent with the findings of Kumar et al. (2023), who reported transportation and mechanized operations as the dominant contributors in conventional potato systems. Similarly, Singh (2022) observed that mechanized field operations contributed significantly to emissions in Himachal Pradesh. In order to reduce emissions, farmers in rural areas can consider pooling transport resources, using more fuel-efficient tractors, reducing the number of trips by planning bulk movements of inputs and produce, and setting up shared input storage facilities closer to the fields to cut down on travel distance. These strategies not only reduce the carbon footprint of potato production but also align with India's Nationally Determined Contributions (NDCs), which aim to lower the emission intensity of GDP by 45% by 2030, thereby promoting climate-resilient and low-carbon agriculture.

The land preparation operation had significant carbon emissions, mainly from machinery (169.65 kg CO_2e), followed by diesel (116.37 kg CO_2e) and tractor use (112.96 kg CO_2e). In contrast, human labor contributed minimally (1.04 kg CO_2e). Planting emissions were dominated by seed use (345.6 kg CO_2e), along with modest emissions from machinery and labor. The high seed-related emissions are comparable to Bharadwaj (2023), who emphasized seed sourcing and preparation as substantial contributors in life cycle assessments of organic potato systems. The emission can be reduced by adopting conservation tillage practices, ensuring proper machine maintenance to improve fuel efficiency, and using seeds at recommended rates to avoid excess input use.

Fertilizer application contributed 184.47 kg CO_2e, primarily from chemical inputs. This aligns with Pathak et al. (2014), who identified fertilizers as a consistent emission source in Indian agriculture. Emissions from intercultural operations, digging and rooting, and irrigation were relatively low, primarily due to manual labor involvement. The total emissions from all operations summed to 1712.88 kg CO_2e, which can be reduced by integrating organic manures and encouraging the use of biofertilizers.

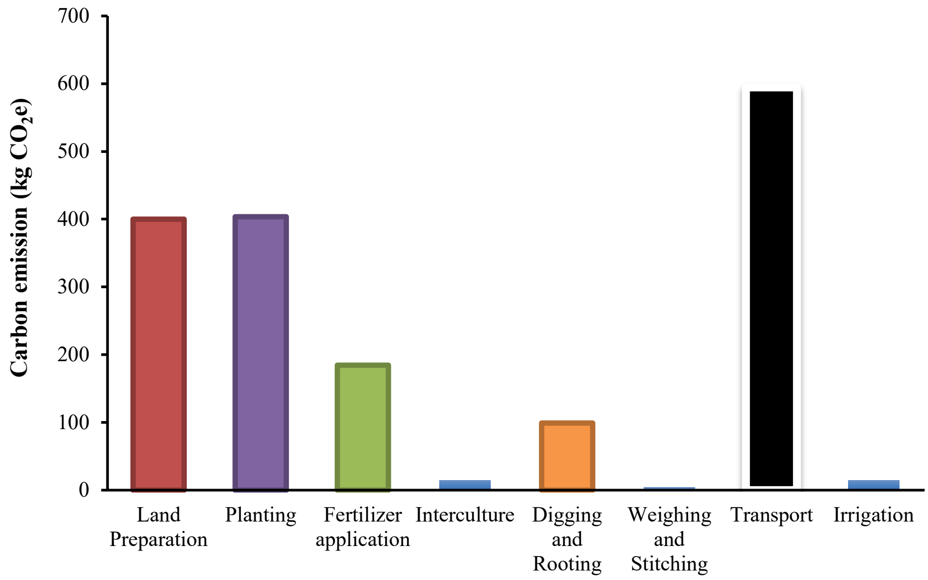


Figure 5 Total carbon emission in each operation for potato production

Table 3 Emission of carbon (kgCO₂e) from various sources for the production of Potato crop

Source	Carbon emission (kgCO$_2$e)	Percentage (%)	p value
Human	117.00	6.82	0.739
Machinery*	858.92	50.15	0.302
Fertilizers	183.39	10.70	0.509
Seed	345.60	20.17	0.527
Fuel*	209.12	12.21	0.386
Total	1714.03		
Output (t ha^{-1})	12.44		
Emission Intensity (kgCO$_2$e ton^{-1})	137.69		

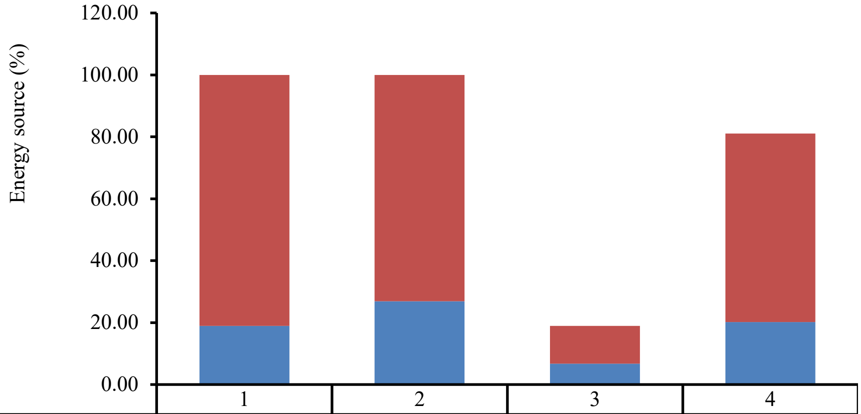
Note: * indicates sources for which carbon emissions were found to be statistical significant ($p \leq 0.05$) across study area.

In terms of the various sources as depicted in Table 3, the machinery use accounted for over half of the total emissions i.e., 50.15% or 858.92 kg CO_2e of the total emissions reinforcing its critical role in emission mitigation strategies, as also highlighted by Jat et al. (2019). The use of seed for potato production contributes 345.6 kg CO_2e, representing 20.17% of the total emissions. This substantial percentage indicates that seed sourcing and associated processes are important factors in emissions and should be carefully considered, following the recommended rate to limit carbon emissions without affecting productivity. In addition, minimizing redundant field trips, using fuel-efficient transport machinery can jointly help reduce emissions without affecting productivity.

The fuel use contributes 209.12 kg CO_2e, or 12.21% of the total emissions. Fertilizers contribute 183.3 kg CO_2e, equating to 10.70% of total emissions. The farmers in the study area did not follow the recommended rates, believing that increased input would lead to higher production. However, this practice has an adverse effect on the environment, releasing substantial amounts of carbon into the atmosphere. The emissions from human labour were 115.94 kg CO_2e and 6.76% of the total, are the smallest but still notable, illustrating that while human-related emissions are lower, they are not negligible.

In terms of various categories of sources of emission (Figure 6), the indirect source contributed 81.02% carbon emission while as direct sources constituted 18.98%. The non-renewable source was extensively used which resulted in the carbon emission to the tone of 73.05% and 22.85% of carbon emission was observed from renewable sources for the production of potato.

The total production of 12.44 t ha^{-1} was observed for the study area using various inputs, which corresponded to an emission intensity of 137.69 kg CO_2e per tonne. In other words, 137.69 kg of carbon is emitted for every tonne of potato produced in the subtropical region of Jammu.



	1	2	3	4
Indirect/Non renewable source emission	81.02	73.05	12.21	60.85
Direct/Renewable source emission	18.98	26.95	6.77	20.18

1. Direct source vs Indirect 2. Renewable source vs Non- renewable 3 Direct renewable source vs Direct non-renewable source 4. Indirect non-renewable source vs Indirect renewable source

Figure 6 Emission sources grouped under different categories for the production of potato

3.2 Operation wise carbon emission in relation to input energy

In terms of input energy consumption for the production of potato (Table 1) estimated using different energy coefficients (Khar and Zaffar, 2023). The comparative details related to the carbon emission and energy inputs are represented in the Table 4.

From Table 4, it was observed that the most energy-intensive operation was fertilizer application, which, however, was not the case for carbon emissions during potato production. The lower carbon emission associated with fertilizer application can be attributed to the fact that the estimation was based only on field measurements, with a boundary set to account for emissions within the field (Tier I). In addition, the fertilizer application requires a significant amount of labour for uniform distribution, which peaks the energy consumption due to the increased man-hours involved. However, the carbon emissions remain minimal because human labor does not significantly contribute to emissions (Figure 7). Similar findings were reported by Inumula et al. (2020), who noted high energy but low emissions for labor-intensive operations. The correlation analysis also revealed a weak correlation between input energy and carbon emissions (R = 0.16) in the subtropics of Jammu which were in line with finding s from Jat et al. (2019) and Kumar et al. (2023), reinforcing the complex interaction between energy type and emissions.

Table 4 operation wise carbon emission and energy consumption for the production of potato

S.No.	Operation	Carbon emission ($kgCO_2e$)	Energy input (MJ ha^{-1})
	Land Preparation	400.02	2203.39
	Planting	403.63	561.20
	Fertilizer application	184.47	8569.00
	Intercultural	14.30	148.88
	Digging and Rooting	99.06	1032.20
	Weighing and Stitching	3.82	69.77
	Transport	594.56	1847.34
	Irrigation	14.19	258.72
	Total	**1712.88**	**14690.50**

The operations of land preparation and transportation both showed significantly higher values for energy consumption (MJ ha^{-1}) as well as carbon emissions ($kgCO_2e$), with values of 2203.39 MJ ha^{-1} and 400.02 $kgCO_2e$ for land preparation, and 1847.34 MJ ha^{-1} and 594.56 $kgCO_2e$ for transportation, respectively. The increased pattern of both energy consumption and carbon emissions can be attributed to the use of machines operating on diesel fuel, which results in higher carbon emissions relative to energy input.

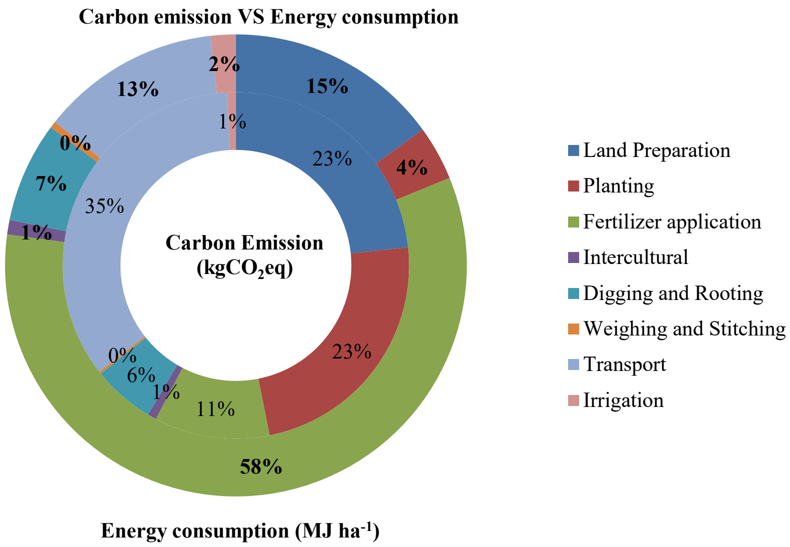


Figure 7 Carbon emission in comparison to the energy consumption for the production of potato

3.3 Limitations

The study offers important insights into the operation-wise carbon emissions associated with potato cultivation in subtropical conditions. However, some limitations need to be acknowledged to strengthen the overall scope of emission assessment. The current analysis was restricted to a Tier I boundary, focusing only on direct field-level emissions. As a result, emissions linked to upstream processes such as the manufacturing of fertilizers, seeds, and machinery, as well as downstream activities like packaging, storage, and transportation beyond the farm gate, were not considered. Their exclusion may lead to a partial estimation of the total carbon footprint. Furthermore, the findings represent a single cropping season, which does not account for annual variations influenced by changing weather patterns, soil dynamics, and management practices.

3.4 Future research

The future studies should aim to broaden the analytical scope by incorporating Tier II and Tier III boundaries, which would allow for a more holistic carbon footprint evaluation. This includes accounting for emissions embedded in input manufacturing, machinery lifecycle, and post-harvest processes using life cycle assessment (LCA) frameworks. Additionally, there is a need to develop localized emission coefficients for tractors, irrigation systems, and other farm machinery commonly used in hill agriculture and subtropical regions, as these tools and practices differ significantly from those in plains or industrial settings. Such region-specific data would improve the accuracy and relevance of emission estimations. Moreover, comparative assessments across various farming systems including conventional, organic, integrated, and conservation-based approaches under uniform agro-climatic conditions could help identify viable low-emission strategies tailored to specific regional needs and resource availability.

4 Conclusion

This study evaluated carbon emissions from potato cultivation across four subtropical villages in Jammu, offering valuable insights into the sources of emissions across various farming operations. The total carbon emission was estimated at 1712.88 kg CO_2e per hectare, with transportation (594.56 kg CO_2e), planting (403.63 kg CO_2e), and land preparation (400.02 kg CO_2e) identified as the highest-emitting operations. Among emission sources, machinery use alone contributed 50.15%, highlighting its dominant role in the overall carbon footprint. A weak correlation (R = 0.16) was observed between total energy input and carbon emissions, indicating that manual operations—though energy-intensive—are considerably less carbon-intensive than fossil fuel-based mechanized activities. These findings emphasize the need to move beyond conventional mechanization and promote low-carbon, energy-smart agricultural practices. Mechanization should be made more sustainable by adopting fuel-efficient machinery, renewable energy sources, and optimized operation planning that maintains both productivity and environmental integrity. The study also supports India's climate commitments under the Nationally Determined Contributions (NDCs) by identifying key emission hotspots and proposing practical mitigation strategies aligned with climate-resilient agriculture. Importantly, the findings highlight that while reducing emissions may involve trade-offs with crop productivity, sustainable intensification through efficient input use, biofertilizers, and conservation practices can mitigate emissions without compromising yields, thereby aligning environmental and food security goals.

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