Quantifying the Spatial Sustainability Threshold of Conventional Potato Distribution Logistics

Arvind Bhardwaj[1*], *Rohit* Kumar[1,2], *Lakhwinder Pal* Singh[1], *Gurraj* Singh[1]
[1]Department of Industrial and Production Engineering, Dr B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India
[2]College of Agriculture, Purdue University, West Lafayette, Indiana, United states of America

Abstract. While the environmental effects of agricultural development are widely understood, the ecological cost associated with the regional distribution of substantial supplies in emerging countries is still a major unknown. The current utilizes a cradle-to-market Life Cycle Assessment (LCA) to evaluate the environmental burden of the conventional potato supply chain originating from the Punjab province, India to nationwide locations. By using a one hectare as afunctional unit and a mean yield of 24.45 t/ha, the study models the impacts across three geographic distribution tiers Local, Regional, and Distant Metro respectively. SimaPro 10.1.1 and the ReCiPe 2016 Midpoint (H) approach were used to characterize the environmental effect across 18 categories. The results show a "Hotspot Inversion" as the distribution radius grows. The farm-gate baseline Global Warming Potential (GWP) of 2007.67 kg CO_2 eq/ha increases by 98.82% at the regional hub and 459.96% at the distant metropolitan market. A critical analytical contribution of this study is the identification of a "Sustainability Threshold", the point where logistical emissions replace agricultural practices as the primary environmental hotspot. Beyond this threshold, the reliance on diesel-powered Light Commercial Vehicles (LCVs) results in a surge of Terrestrial Ecotoxicity and Fossil Resource Scarcity, driven by the high energy intensity of small-scale road freight. The findings show that the environmental benefits of high-yield farming methods in Punjab are substantially offset by logistical inefficiencies in long-distance distribution.

1 Introduction

The growing worldwide need for food, fiber, and biomass places a significant burden on logistical supply lines that move products across great distances. This growth not only raises the use of limited resources, but it also produces a vicious cycle of environmental strain [1]. As global food systems grow, the environmental implications of transportation, sometimes known as "food miles," become a substantial input to the overall life cycle impact of agricultural goods. This issue becomes even more essential when the commodities are very perishable, such as potatoes, which need immediate treatment and specialized logistics to avoid post-harvest losses.

* Corresponding author: Bhardwaja@nitj.ac.in

Punjab is agrarian state, widely recognized as the "Potato Basket" of India, contributing a massive portion of the national production. However, there remains a notable lack of research regarding the post-harvest supply chain within developing countries like India. Prior research has identified that nearly 15–20% of potatoes in India are lost due to poor post-harvest management and logistical inefficiencies. Despite this, environmental data for these hotspots is unavailable because most studies are restricted to the farm-gate. Prior research shows that the environmental burden shifts from the source (the farm) to the logistical supply chain as products move toward the consumer end [2]. This system is highly complex because the factors such as vehicle type, distance, traffic congestion, and road conditions all play a direct or indirect role in increasing total emissions of the supply chain. Therefore, it is essential to perform an assessment that counts emissions right from the point of pickup to the final market or customer end.

Life Cycle Assessment (LCA) is the standardized method typically used to quantify environmental impacts with respect to a process or product throughout its selected boundary system [3]. The methodology go beyond the tailpipe emissions to include embodied carbon from other phases involved in the process/product, enabling comparisons between transport modes to quantify, measure, and minimize overall GHG emissions. When we apply LCA to assess the sustainability of food systems, the transportation impacts which is one of the major contributors, are heavily impacted by the management of food supply chains. Food systems should not be seen as simply "conventional" or "alternative" chains, but rather as linked logistical channels working at various geographical scales. In this environment, the Punjab potato industry's logistics network does not operate independently; rather, it overlaps with several regional and national distribution channels as the produce flows to distant markets. Applying LCA to these interconnected routes explains how transportation distance, mode choice, and network layout influence ecological sustainability. While LCA offers a strong foundation for assessing transportation-related emissions, environmental performance alone does not establish sustainability. Water pollution, rural economic resilience, and landscape modification are all important issues for food production and distribution systems' sustainability [4].

The burden of logistics production is often identified as a key environmental obstacle for the transportation of perishable vegetables in both global and local life cycle assessment studies that are currently being conducted. Mattsson and Wallén (2003) investigated the supply chain for pest-free potatoes in Europe. They discovered that although the cultivation phase was the primary contributor to eutrophication and acidification, the distribution phase emerged as a key hotspot for climate change owing to the fact that it required a significant amount of resources, such as fossil fuels [5]. The load regularly varies in bigger geographic settings such as India, as this was also noted in our earlier research [6]. In a similar vein, Gunady et al. (2012) demonstrate that highway-based transport distances can effectively double the total energy demand of the product for high volume vegetable supply chains [7]. Furthermore, transportation is responsible for nearly half of the cradle-to-retail emissions for crops that are transported over long haul distances.

With in the Indian domestic market it has been established by the Central Potato Research Institute (ICAR-CPRI) that there are major post-harvest management gaps. The institute has also noted that around 15–20 percent of the yield is wasted yearly owing to logistics and storage inefficiencies [8]. Additionally, the special environmental intensity of the Indian road freight sector, which is defined by a large dependence on diesel-powered light commercial vehicles, results in a higher emission factor per ton-kilometer in comparison to fleets used by industrialized nations [9]. These established results highlight a key research need, which is the identification of the geographical "sustainability threshold." This threshold is the point at which the environmental advantages of Punjab's high-yield agriculture are rendered ineffective due to the carbon-intensive logistics that are necessary for distribution on a national basis. By extending the boundary from the farm-gate to metropolitan markets, this study addresses that gap and provides a comprehensive view of the spatial environmental footprint of the Indian potato supply chain.

In this particular instance, the key research gap that has been highlighted is the lack of high-resolution geographical data about the point at which the environmental efficiencies that have been achieved on the farm are removed by the costs of logistics. In spite of the fact that the consequences of farm gates are well recognized, there is a "missing link" in the process of comprehending the environmental crossing sites in the context of India. One of the most interesting aspects of this research is that it able to pinpoint a certain "Sustainability Threshold" which helps the finding in nuance way of understanding. This paper, in contrast to typical evaluations, gives a mathematical "break-even" point for the Indian potato supply chain. It demonstrates precisely where the environmental identity of the food transitions from that of an agricultural output to that of a logistical commodity.

Therefore, the purpose of this study is to broaden the scope of the cradle-to-farm gate border to include a full cradle-to-market system. This will be accomplished by analyzing the environmental footprints that are associated with three separate metropolitan tiers: the local, the regional, and the distant metropolitan areas. Even beyond the realm of academic theory, the relevance of this study extends to the realm of public policy. Through the quantification of the "Hotspot Shift" and the exponential rise in ecotoxicity over long distances, this study provides a data-driven roadmap for the development of "Green Food Corridors." Additionally, it highlights the environmental necessity of modal shifts from road to rail for India's long-haul agricultural distribution.

2. Materials and Methods

2.1. Goal and Scope Definition

The primary goal of this study is to assess the environmental impact of the conventional potato supply chain in India's Northern Plains, from the farm gate to three distinct city market levels. The study aims to identify the geographic border at which logistical constraints begin to overwhelm the environmental characteristics of the product.

2.2. Functional Unit

To stay within the agricultural baseline, a land-based Functional Unit (FU) of one hectare (1 ha) of potato production was used. This method allows for a direct assessment of the environmental pressures imposed by a specific unit of Punjab agricultural land as its output flows across the national supply chain. Based on primary field data from the Jalandhar district, a mean conventional yield of 24.45 metric tons per hectare (t/ha) was used for supply chain normalization purposes.

2.3. System Boundary

Fig 1 depicts the "Cradle-to-Market" boundary system that was employed in the study. This comprises the cultivation phase, which involves on-farm agricultural operations such as soil preparation, planting, fertilizer, crop protection, irrigation, and harvesting and distribution. Post-harvest logistics from the Jalandhar regional headquarters to three specific areas. The border concept eliminates cold storage and retail activities in order to focus on the carbon footprint of road freight.

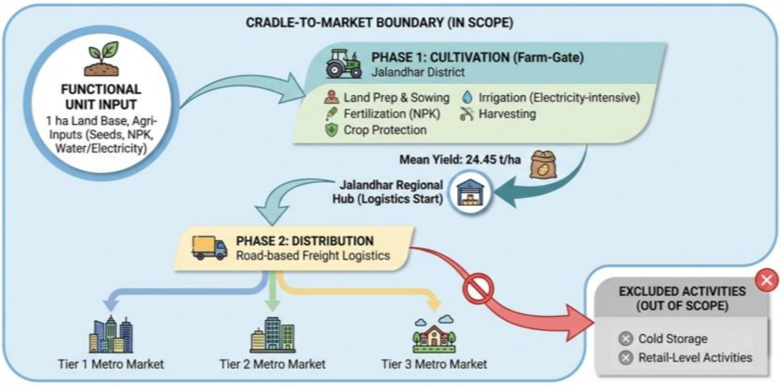

Fig. 1. System boundary of selected system under intervention

2.4. Spatial Scenarios and Transport Modeling

The research uses three geographic distribution tiers to describe the spatial environmental impact of the Punjab potato supply chain (Table 1). The local tier (80 kilometers) represents the intra-state regional catchment and aggregation point for produce from the Jalandhar cluster. According to Kaur and Sidhu (2015), while potato farmers from the Jalandhar region primarily sell within a 0–30 km primary catchment comprising Jalandhar, Kapurthala, Phillaur, and Nakodar mandis, the larger regional hubs of Ludhiana and Amritsar mandis fall within a secondary catchment (30–80 km), accessed mainly for bulk or price-driven transactions [9-11]. The regional tier (379 km) focuses on Delhi NCR, notably Azadpur Mandi, Asia's biggest redistribution center and the principal gateway for Punjabi goods to the rest of India. Finally, the farthest metro tier (1,764 km) from Mumbai acts as a logistical "stress test" to assess long-haul, diesel-intensive inter-regional commerce and determine the sustainability threshold of road-based distribution. All distances have been measured from the Bolina farm, Karari village, Jalandhar, which is the point of origin for the previously validated farm gate analysis [6]. This multi-layered selection accurately represents India's hierarchical agricultural logistics, from local aggregation to national distribution.

Table 1. Logistics Inventory of the selected system under investigation

Distribution Tier	Destination	Distance (km)	Justification
Local*	Punjab mandis	80 km	Full mandi catchment
Regional**	Delhi NCR	379 km	National redistribution hub
Distant Metro***	Mumbai	1,764 km	Long-haul stress scenario

*Local distance has taken to cover realistic upper bound of direct farmer/mandi sales
**The regional tier represents supply to Delhi NCR, the dominant wholesale redistribution hub for Punjab-grown potatoes.
***Mumbai was selected to represent distant metro supply, characterizing long-haul, diesel-intensive food distribution typical of India's inter-regional produce trade.

2.5. Life Cycle Inventory and Data Sources

Primary data for the cultivation phase was sourced from field surveys of potato farms in Punjab (2021–22 season). Background data for the techno sphere including the manufacturing of fertilizers, pesticides, and vehicle operations was obtained from the Ecoinvent v3.7.1 database as mentioned in detail in our previous study [6]. The transport process was modeled using the "Transport, freight, lorry 3.5-7.5 metric ton, EURO 6 {RoW}" dataset, which provides a representative proxy for the Indian vehicular fleet's emission profile [12].

2.6. Life Cycle Impact Assessment

The environmental impacts were calculated using SimaPro 9.1.1 software coupled with Eco invent and Agri footprint database. The ReCiPe 2016 Midpoint (H) method was selected for its comprehensive characterization of eighteen impact categories, including Global Warming Potential, Terrestrial Ecotoxicity, and Fossil Resource Scarcity. This method provides a balanced Hierarchist perspective, suitable for evaluating long-term environmental trade-offs in agricultural supply chains [6,7].

3. Results and Discussion

3.1. Environmental Baseline at the Farm-gate

The life cycle assessment of traditional potato cultivation in our prior study (Kumar et al 2023) in northwest region in Punjab reveals a significant hotspot among cradle to farm gate per hectare emissions. It has been stated that that the fertilization and sowing phases appear to be more dominant as compared to other phases, which is in confirmation with the historical data available, that highlights the higher contribution of several studies [13-15] have examined the fertilization phase of agricultural operations. The fertilization phase has the most significant influence on climate change, fossil resources as well as all toxicity markers. The GWP of 2007.67 kg CO_2 eq per hectare at the farm-gate has been recorded [6]. As established in prior characterization, the environmental burden at this stage is primarily driven by fertilization and irrigation practices. Other significant categories include Fossil Resource Scarcity (656.6 kg oil eq) and Terrestrial Acidification (14.74 kg SO_2 eq), both linked to the intensive use of synthetic agrochemicals and diesel for farm machinery.

3.2. Impact of Spatial Distribution (Transportation Scenarios)

The transportation scenarios, integrating post-harvest logistics inside the system boundaries considerably raises the environmental profile in all 18 impact areas (see Table 2). The percentage increase and contribution made by all three different transportation scenarios have been illustrated in Fig 2 which highlights a strong distance-dependent escalation of environmental burdens, with long-distance distribution dominating both absolute impact increases and transport contributions across most midpoint categories. As the distribution radius increases from local to urban markets, ecological pressure rises dramatically (refer Fig 3).

- Local Distribution: Transporting the whole yield (24.45 t/ha) to local Punjab markets (within the catchment radius) resulted in a slight GWP increase of 20.86%, reaching

2426.46 kg CO_2eq. Even though the system's border has been extended, the cultivation phase remains the major environmental driver at this distance.

- Regional Distribution: Extending the supply chain to Delhi's regional center nearly doubles the GWP (+98.82%) to 3991.69 kg CO_2 eq., highlighting the importance of transportation in the system. When we approach this catchment radius of potato distribution from the Farmhouse gate, the GWP impact nearly doubles.
- Distant Metropolitan Distribution: The distant transportation scenario (at a distance of 1,764 km) has the greatest impact, with a total life cycle GWP of 11,242.07 kg CO_2 equivalent. This marks a startling 459.96% increase over the farm-gate baseline, showing that the produce's carbon footprint can be multiplied by five through long-distance transportation.

While climate change is the most widely discussed metric, the current study reveals that other categories, particularly toxicity and resource-related indicators, are also on the rise. For example, moving from the farm gate to Mumbai results in a 938.46% increase in ecotoxicity and Fossil resource scarcity increases by 482%. This dramatic rise is directly related to the reliance on Light Commercial Vehicles (LCVs), which are mostly employed for logistics in the selected region. The high yield of Punjab (24.45 t/ha) effectively becomes a "Logistical Burden" when forced through a high-carbon transport network at long haul transportation.

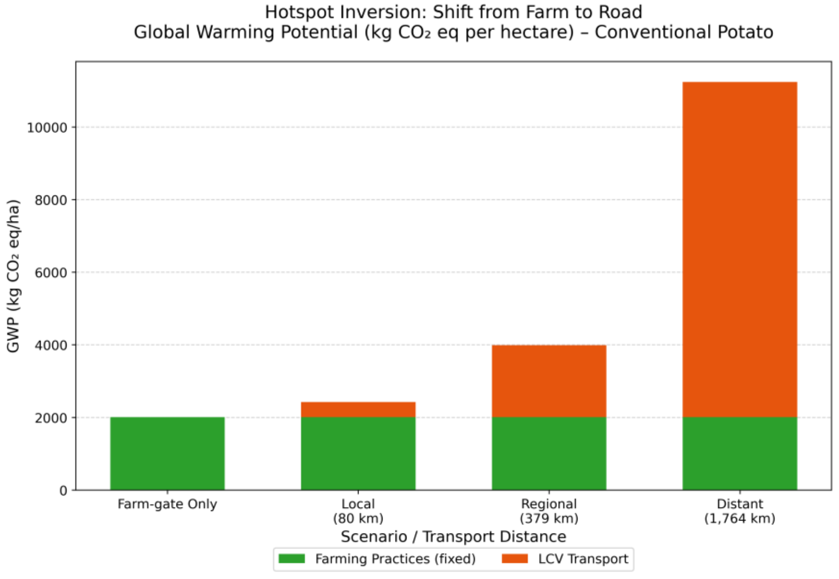

Fig. 2. Global Warming Potential (kg CO_2 eq/ha) contribution of conventional potato w.r.t to transport distance (i.e. local, regional and distant)

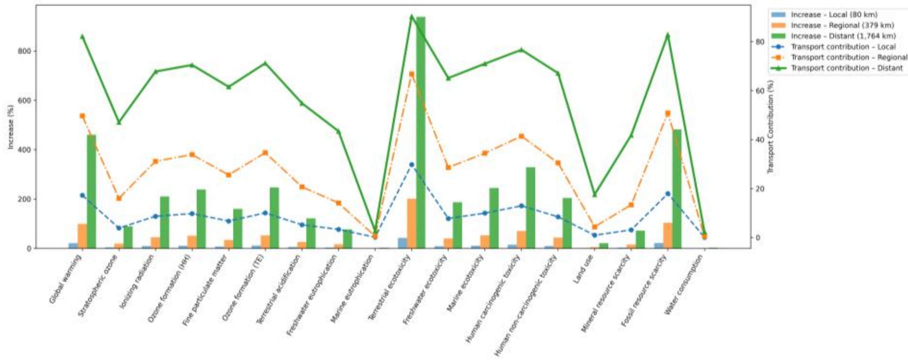

Fig. 3. Increase in environmental impacts and transport contribution across different distribution distances for the conventional potato supply chain.

Table 2. Midpoint characterization of environmental impacts for one hectare of conventional potato production, with extended boundaries from farm-gate to include transportation.

Impact Category	Unit	Farm-gate Only	Farm gate + Local	Farm gate + Regional	Farm gate + Distant
Global warming	kg CO_2 eq	2007.67	2426.46	3991.69	11242.07
Stratospheric ozone depletion	kg CFC11 eq	0.01	0.01	0.01	0.01
Ionizing radiation	kBq Co-60 eq	76.98	84.33	111.78	238.97
Ozone formation, Human health	kg NOx eq	5.6	6.2	8.46	18.95
Fine particulate matter formation	kg PM2.5 eq	5.21	5.58	6.99	13.53
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.71	6.35	8.74	19.81
Terrestrial acidification	kg SO_2 eq	14.74	15.55	18.59	32.67
Freshwater eutrophication	kg P eq	1.09	1.13	1.28	1.94
Marine eutrophication	kg N eq	2.25	2.26	2.27	2.32
Terrestrial ecotoxicity	kg 1,4-DCB	10598.65	15109.51	31968.74	110063.13
Freshwater ecotoxicity	kg 1,4-DCB	91.17	98.89	127.74	261.37
Marine ecotoxicity	kg 1,4-DCB	115.46	128.26	176.13	397.85
Human carcinogenic toxicity	kg 1,4-DCB	68.19	78.35	116.32	292.22
Human non-carcinogenic toxicity	kg 1,4-DCB	3025.16	3305.41	4352.86	9204.78
Land use	m^2a crop eq	1496.97	1511.43	1565.49	1815.9
Mineral resource scarcity	kg Cu eq	29.69	30.66	34.28	51.03
Fossil resource scarcity	kg oil eq	656.6	800.23	1337.08	3823.82
Water consumption	m^3	1047.42	1048.57	1052.88	1072.83

3.3. Identifying the Sustainability Threshold

The key quantitative contribution made by the present research is the identification of the Sustainability Threshold, which was calculated using linear interpolation on the provided data. The threshold distance, or the point at which transportation emissions equal total on-farm emissions, was determined to be 383.52 kilometers as shown in figure 4. These findings are particularly significant for the Punjab-Delhi supply chain (379 kilometers). This is one of the most heavily used and stressed routes for supplying funds to the country's North Indian states. The distribution outside of the Delhi NCR core causes a Hotspot Inversion, in which the farm's internal efficiency (such as optimal fertilizer usage) is statistically insignificant when compared to the external inefficiencies of the transportation network. This indicates that cultivation burden of Punjab farming is only environmentally profitable for North Indian clients under the current logistical systems. To reduce food miles implies the need for food systems grounded in local ecologies and responsive to consumer demands for quality food, hence the growing literature on the benefits of a more localized food supply system.

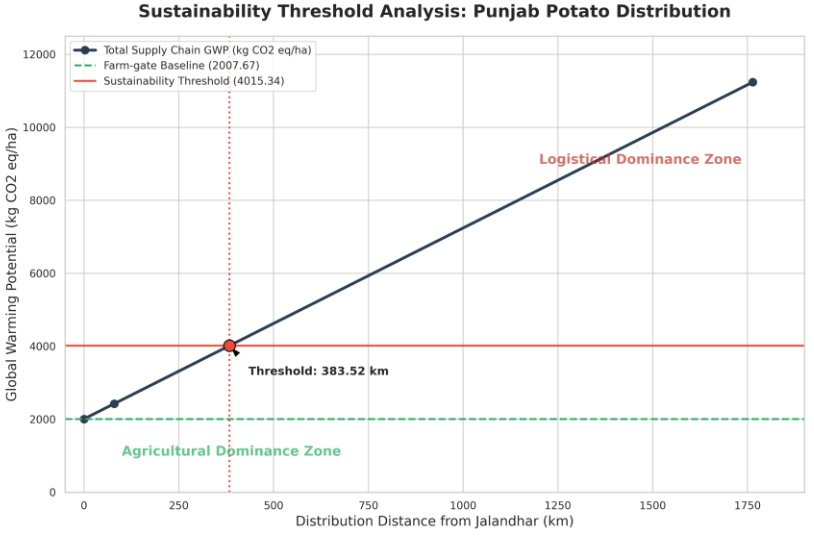

Fig. 4. Logistical break-even analysis for conventional potato distribution from Punjab. The sustainability threshold indicates the distance at which greenhouse gas emissions from transportation equal the total farm-gate emissions.

4. Conclusion

The current study conclusively finds a spatial boundary of sustainability for the Northern Indian potato supply chain. The study identifies a critical logistical "Hotspot Inversion Point." While agricultural activities (fertilization/irrigation) dominate the environmental profile of the 80-kilometer local supply chain, transportation becomes the primary burden as produce reaches the regional hub. Beyond this sustainability threshold, the "farming method" becomes secondary to the high carbon "logistics method”. his results in several critical imperatives for the industry:

- Conventional potato distribution remains environmentally "balanced" only within a regional hub radius. Beyond this, the distribution footprint overshadows all agricultural innovations.

- The current reliance on diesel-powered LCVs for metro-bound supply is a noticeable point for India's climate goals.
- To maintain the sustainability of Punjab's high-yield "Potato Basket," a mandatory shift from Road (LCV) to other possible renewable options is required for any distance exceeding threshold.

5. Limitations of the study

Despite the thorough analysis of the present investigation, certain limitations must be acknowledged. First, the system boundary is limited to a "cradle-to-market" scope, omitting the environmental costs of long-term cold storage, secondary packaging, and retail-level waste management, which might exacerbate the overall life cycle impacts. Second, logistic analysis assumes that only Light Commercial Vehicles are used; however, in actuality, the Indian supply chain may use bigger, more fuel-efficient heavy-duty trucks or multi-modal shifts, which might change the transport-to-farm effect ratio. Finally, while this study identifies a clear environmental "Sustainability Threshold," it fails to account for the economic and social dimensions of sustainability, as well as the potential impact of post-harvest losses during distribution, which continues to be a critical factor in agricultural supply chain efficiency.

6. Policy Implications and Future Outlook

The findings provide a scientific foundation for three distinct policy interventions:

- Zonal distribution strategies would be encouraging regional consumption hubs within catchment radius to optimize the environmental advantages of Punjab's agricultural efficiency.
- Logistics Decarbonization need to focus on electrifying the freight fleet and expanding rail-loading capabilities at wholesale mandis in Jalandhar and Ludhiana.
- Future food labeling in India might include "spatial sustainability" ratings to alert consumers about the environmental impact of the distance their food has traveled.

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