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Carbon Footprint of Fruit Supply Chains

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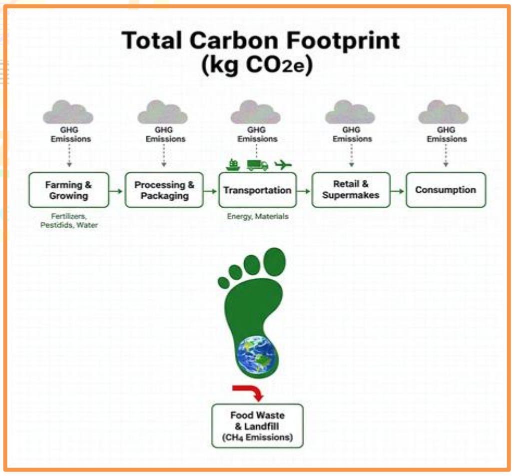
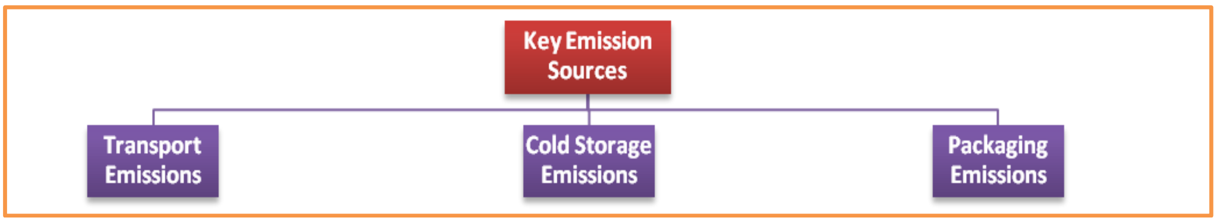
The carbon footprint of the fruit supply chain is a multifaceted issue that spans from cultivation to consumption, with each stage contributing to overall greenhouse gas emissions. Agricultural practices such as the use of synthetic fertilizers, pesticides, and energy-intensive irrigation systems release significant amounts of greenhouse gases, including nitrous oxide, into the atmosphere.

Sustainable farming methods like organic farming, agroforestry, and crop diversification can help mitigate these emissions while enhancing biodiversity and soil health. Post-harvest handling, which includes sorting, washing, cooling, and packaging, also adds to the carbon footprint, particularly through energy-intensive refrigeration and the use of non-biodegradable packaging. Solutions like solar-powered cooling systems and recyclable packaging materials can alleviate these impacts. Transportation, a major contributor to emissions, involves long-distance travel of fruits via fossil fuel-powered trucks, ships, and airplanes, with airfreight being particularly carbon-intensive. Encouraging the purchase of local and seasonal fruits and reducing food waste through better planning and storage can help mitigate these effects.

Environmental Costs of Fruit Production



Fruit production carries substantial environmental costs, contributing 10-30% of total food-related greenhouse gas emissions through intensive resource use and supply chain demands. Life Cycle Assessments reveal transport, refrigeration, and fossil-heated greenhouses as primary hotspots, with imported fruits often emitting 20-96% more CO_2e/kg than local seasonal produce. Global trade amplifies footprints—70% from transport/refrigeration in imports vs minimal for local sourcing—demanding sustainable strategies like seasonal eating and waste heat greenhouses (Wang *et al.*, 2026).



Transport Emissions

- Transport emissions are a key contributor to the carbon footprint of fruit supply chains, impacting road, maritime, and air transport. For fruits like oranges, grapes, and apples, maritime transport accounts for 41-53% of emissions, while road transport contributes 30-37%.
- Transport-related activities, including road and maritime transport, are the main sources of carbon emissions in fruit supply chains.
- In international trade, maritime shipping plays a major role in long-distance transportation of fruits.
- Emissions from ocean freight range from 0.31 to 0.84 kg CO2e per kilogram of fruit, depending on the route. Air freight has a much higher environmental cost, with emissions as high as 11.35 kg CO2e per kilogram of fruit.
- Shortening the supply chain can reduce emissions to 0.87-1.28 kg CO2e per kilogram of fruit.
- Extended storage increases emissions, sometimes doubling the carbon footprint.
- Prioritize maritime transport over air freight, optimize load factors, and reduce empty transport runs to lower emissions in the supply chain

Cold Storage Emissions

The carbon footprint of fruit storage and handling is considerable, with each pallet stored without solar energy emitting 7.52 kg CO_2e daily. Cold storage requires 7.62 kWh of electricity per pallet, but with solar power, emissions decrease to 5.72 kg CO_2e per day. Refrigeration contributes 28–30% of emissions, while transport accounts for 70–72%. Cold storage, distribution, and retail facilities contribute 12%, and losses/wastage add 9%. For fruits like table grapes, maritime shipping is responsible for 46% of emissions in pre- and post-carriage stages. Short cold chains for fruits such as oranges, grapes, and apples result in carbon footprints between 0.87 and 1.28 kg CO_2e per kg of saleable fruit. Extending storage increases emissions, with six months of controlled atmosphere storage nearly doubling emissions for apples.

Packaging Emissions

Fruit packaging significantly impacts its carbon footprint. Open stock bags have the lowest CO_2 content, at 2.28 g CO_2 per kg of fruit, while checkout bags can triple this footprint. Boxed packaging has the highest footprint (168.53 g CO_2/kg), driven by polymers like PET (49.39 g/kg) and additives like absorbent pads. Other packaging types, such as bagged and bottled forms, fall in between, with bottled containers contributing 128 g CO_2/kg. Reducing package sizes from 1-2 kg to 0.1-0.25 kg increases the normalized plastic footprint by 98%, highlighting the need for more efficient, larger packaging formats. The adoption of mono-material packaging and minimizing labels can improve recyclability and reduce embodied emissions. Moreover, eliminating checkout bags could cut an additional 7 g CO_2/kg from the supply chain's overall emissions, underscoring the need for better packaging design to minimize plastic waste and carbon footprints in the fruit industry.

Measurement Tools: Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) serves as an essential tool for evaluating the carbon footprint throughout the entire fruit supply chain, from farm production to the consumer. By quantifying greenhouse gas emissions at each stage, LCA helps to pinpoint critical areas where emissions can be reduced, thereby guiding more sustainable practices. The average cradle-to-farm gate carbon footprint for fruits is approximately 0.503 kg CO_2-eq per kilogram of fruit, although this value can vary depending on the type of fruit and agricultural practices employed (Du Plessis *et al*., 2024). A meta-analysis of various studies on fruit supply chains reveals a mean cradle-to-farm gate carbon footprint of 0.503 ± 0.365 kg CO2-eq per kg of fruit. When the assessment is extended to include the full life cycle—from cradle-to-retail and cradle-to-grave—the average carbon footprints increase. Specifically, the cradle-to-retail footprint is 0.743 ± 0.193 kg CO_2-eq per kilogram of fruit, while the cradle-to-grave footprint rises to 1.257 ± 0.886 kg CO_2-eq per kilogram of fruit.

Fruit Supply Chain Stage	Typical Emission Contribution	Reduction Strategies
Farming (inputs, irrigation)	**40-60%**	**Precision fertilizers, efficient irrigation**
Transport	**10-30% (higher if by air)**	**Local/seasonal sourcing, sea/road over air**
Storage/Processing	**15-25%**	**Controlled atmosphere systems**

Local Sourcing Benefits

Local sourcing helps reduce carbon footprints by cutting down on transport emissions since fruits travel shorter distances from farms to consumers. Research shows this approach works best when not using fossil fuels for greenhouse heating, keeping the produce fresher and more nutritious. It also supports eco-friendly farming methods like crop rotation, further minimizing environmental impact. By reducing long-haul transport (which is responsible for 10-20% of emissions), local sourcing only requires short truck trips under 100 km. For example, seasonal local apples emit only 0.2-0.5 kg of CO2 per kilogram, compared to over 2 kg for imported ones. Additionally, less energy is needed for storage and less waste is produced because the produce moves faster.

Aspect	Global Chain	Local Sourcing
Transport	**5-10 kg CO2e/ton-km**	**<1 kg CO2e/ton-km**
Total CO2e/kg Fruit	**1-5 kg**	**20-50% less**
Tools Used	**Full LCA (cradle-gate)**	**Same, with regional data**

Solar-Powered Storage

LCA follows ISO 14040 standards, scoping the fruit supply chain (e.g., apples or citrus), collecting inventory data on energy use and emissions, assessing impacts like global warming potential (GWP), and interpreting results. Key stages include cradle-to-gate (farm to storage) and full chain analysis, where storage often accounts for 10-30% of total emissions due to refrigeration energy demands. Tools like SimaPro software integrate data on electricity, refrigerants, and food waste to quantify CO2 equivalents.

Aspect	Conventional Storage	Solar-Powered Storage
Energy Source	Grid/diesel (0.5-1 kg CO2e/kWh)	Solar (near-zero operational emissions)
Annual Emissions (5T fruit)	50-150 tonnes CO2e	10-50 tonnes CO2e
Post-Harvest Loss Reduction	20-40% waste	<10% waste, extending shelf life
Lifecycle GWP (per kg fruit)	0.5-2 kg CO2e	0.2-0.8 kg CO2e

Case Comparison: Imported vs Local Fruits

Fruit/Aspect	Local Fruits (kg CO_2e/kg)	Imported Fruits (kg CO_2e/kg)	Main Difference
Apples	0.2-0.5	0.88 (short SA-Scotland)	Transport + refrigeration
Oranges	0.3-0.6	0.87 (short SA-Scotland)	Long-haul shipping

Table Grapes	0.4-0.7	1.28 (short SA-Scotland)	Lightweight pallet emissions
Mango (example)	N/A	0.5-1.0 (Brazil)	Tropical production + freight
Transport Emissions	Low (short distances)	High (70% total, air/sea)	Distance dominates imports
Production Emissions	Varies; heated = high	Lower tropics, no heating	Greenhouse fossil fuels 10-19x
Storage/Refrigeration	Minimal cold chain	20-30% total; +24-96% long	Duration critically increases
Average Total	20-50% lower overall	0.87-1.28 base	Seasonal local best strategy

Way to minimize carbon foot print in fruit supply chain

- Prefer shipping fruits by sea over air freight to reduce CO_2 emissions, as maritime transport is more energy-efficient.
- Maximize the load capacity of transport vehicles to ensure that emissions are spread over a greater amount of fruit.
- Reduce unnecessary empty return trips by better planning transportation routes, which helps cut down on emissions.
- Improve the energy efficiency of refrigeration systems used during transport to lower their environmental impact.
- Shorten the supply chain by reducing the distance between producers and consumers, cutting down on transportation-related emissions.
- Use renewable energy sources like solar or wind power for transportation and refrigeration to reduce reliance on fossil fuels.
- Source fruits locally to avoid the emissions associated with long-distance transportation.
- Use eco-friendly, recyclable, or biodegradable packaging to reduce the environmental impact of packaging waste.
- Encourage sustainable farming practices like crop rotation and organic farming to lower the carbon footprint of fruit production.

Conclusion

Fruit production in Madhya Pradesh comes with significant environmental costs, mainly due to high food loss and waste (FLFW) in supply chains, especially for crops like tomatoes. At the farm level, around 15% of the produce is lost, and an additional 12% is wasted at retail. This contributes to higher carbon emissions, particularly from horticultural waste, adding up to a substantial environmental impact across the country. These losses highlight the urgent need for improved post-harvest practices to reduce waste and lower the carbon footprint throughout the fruit supply chain.

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