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Evaluating sustainability of the surimi supply chain in India: a life cycle assessment approach

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Abstract
Purpose Being a primary product for a multitude of processed seafood, the ecological impacts of surimi have been less noted, despite its global supply dominance, especially in India. Life cycle assessment (LCA) evaluates the environmental sustainability of existing supply chain by comparing it with two other supply chain alternatives. The ecologically understudied and fragmented nature of the existing Indian surimi supply chain necessitates the authors to highlight the significance of supply chain localizations and the reductions obtained in ecological impacts. The current study will show the direction for developing strategy(s) to improve the environmental sustainability in Indian stance.

Methods A cradle-gate approach of LCA is adopted right from fishing to an export market. Different supply chain alternatives such as the current state and two different states with different localizations and downstream alternatives (i.e., Scenario 1 with partial localizations and Scenario 2 with complete localizations) are analyzed to study the impacts. An economic analysis of these scenarios is also carried out to check the competency of the proposed alternatives for economic sustainability.

Results and discussion Eleven environmental impacts considered for analysis under the existing supply chain scenario denote that the process of fishing has an average environmental impact of 74%. However, the inclusion of downstream operations such as distribution in the LCA analysis reveals a significant share of environmental impact averaging 53% from fishing and 34% from distribution for the 11 environmental indicators considered. A detailed assessment of the various alternatives considered reveals vital improvements for both Scenario 1 and Scenario 2 in human carcinogenic toxicity (8% and 16%), fossil resource scarcity (8% and 20%), and global warming potential (GWP) (6% and 16%), respectively, in comparison to the current state. A carbon footprint assessment of the complete surimi supply chain to an export market (considered in this study) via ship freight denotes reduction in footprint values from 4.67 kg CO₂ equivalent/kg (existing state) to 4.43 kg CO₂ equivalent/kg (Scenario 1) and 4.06 kg CO₂ equivalent/kg (Scenario 2), respectively. The economic analysis reveals maximum fiscal gains of 9.83% and 13.31% in Scenario 1 and Scenario 2 respectively.

Conclusion Results highlight that the introduction of supply chain localizations in the Indian surimi scenario can reduce environmental impacts and improve economic savings. Among the assessed alternatives, Scenario 2 is found to be the best sustainable alternative with reduced environmental impacts and improved savings.

Keywords Life cycle assessment · Surimi supply chain · Supply chain localization · Environmental sustainability · Economic analysis

1 Introduction

India ranks third globally in fish production (NFDB 2019), posing self-reliance, exporting 1.3MMT (Bureau 2018), and earning $7.08 billion in the year 2017–2018 (Nambudri 2018). The rising global consumer market for seafood has improved the demand for processed seafood products such as “surimi.” Generated from fish muscles after deboning, the fish meat retrieved is washed with water and blended with cryoprotectants to provide an extended frozen shelf
life (Park et al. 1997). Gaining substantial importance in the global marketplace (Sultan et al. 2020), Indian surimi constitutes 2.5% of the processed seafood export earnings (Dasgupta et al. 2019). India contributes 2% to the soaring global surimi demand of 705,051MT (Trade Map 2019). The worldwide surimi produces, getting affected by the decrease in US Pollock stocks (Seaman 2018), has shifted demands to species such as threadfin bream and other tropical fishes from Asia for satisfying this mounting demand (Surimi market update 2018). This has hence positively influenced nations such as India1 which despite its lower global surimi contribution has recorded a 5% increase in surimi exports in the last 5 years. The low-cost advantage of Indian surimi owing to its low whole fish pricing and cheap labor (Routroy et al. 2019) has positioned it as a preferred source globally. This gets evident from the increasing number of surimi processing plants being set up in the country (FAO 2018).

Surimi processing in India generally uses pink perch, ribbon fish, lizard fish, bronze croaker, reef cod, and crocker fish. Being an intermediate material for producing numerous seafood products (Park 2005), surimi production generates fish head and viscera called Rest Raw Material (RRM) that are used by secondary processing industries to produce value-added products (VAPs). Despite its growing stance in the global market, surimi production in India severely lacks operational sustainability considering the depleting resources, growing mindful clients, and increasing global demand for sustainable products (Galarraga and Markandaya 2004).

Seafood production being an energy intensive operation (Parker et al. 2018) consumes 1220 Mn liters of fuel (Boopendranath 2006) and releases 134 MT of CO\textsubscript{2} in the atmosphere (Vivekanandad 2013). With global CO\textsubscript{2} emissions increasing to 36 Billion tons per year (Ritchie and Roser 2017), the fishing sector is not often discussed in terms of its carbon footprint. This becomes further evident from the inadequate studies on environmental impacts caused from seafood (Clune et al. 2017) that are found in academic literature (i.e., 90 research articles) from the Scopus database in the last two decades (Ruiz-Salmón et al. 2020). Hence, it does not allow us to have a clear understanding of the environmental impacts caused from seafood production. The life cycle assessment (LCA) methodology is a competent quantifying tool for measuring environmental sustainability effects such as acidification, climate change, eutrophication, and ecotoxicity (Ziegler et al. 2016; Laso et al. 2018a, b). The results obtained from LCA assist in recognizing and benchmarking environmental hotspots associated with the life cycle of a product. A comprehensive analysis of the entire fisheries supply chain using LCA was carried out by Avadì and Fréon (2013). However, it was observed that the amount of work carried on LCA on processed seafood was limited (Vázquez-Rowe et al. 2012). Limited research has also been reported from literatures within India related to the assessment of environmental impacts from fishing despite its global stance. Das and Edwin (2016) carried out an LCA on sardines in India; Vivekanandan (2013) conducted a carbon footprint assessment of Marine fishing boats in India; Boopendranath and Hameed (2009) carried out an energy analysis of traditional non-motorized gill net operations; Edwin and Hridayanathan (1997) calculated the energy efficiency in the ring seine fisheries in the state of Kerala.

This article augments its contribution to the growing domain of seafood LCA literature, by assessing the ecological impacts using a cradle-gate approach (i.e., fishing-surimi processing). The research article quantifies the operation-wise environmental effects along the Indian surimi supply chain by understanding the operatives of a leading surimi producer and associated fishing boats supplying fish to the case organization. This assessment is initiated by dividing the entire supply chain into phases to make impact documentation easier. Data considered for the LCA model is based on the information obtained for the year 2018.2 The research is expanded further considering the impacts caused during distribution to a leading international market. The results obtained, being one of its type in the Indian context, are synchronous with LCA studies carried out at the international level (Almeida et al. 2014; Avadì et al. 2014) and number of studies on fish processing in specific (Thrane 2006; Schmidt and Thrane 2007). Inclusion of product distribution, however, transforms the way results are deliberated (refer to Sect. 3.3), requiring further meditative solutions for reducing the allied impacts.

Through this research, the authors make an initiative to interpret the environmental impacts emitted from the Indian surimi supply chain considering various supply chain downstream alternatives. The deliverables from this research put forward a framework highlighting achievements of increased sustainability efficiency by localizing supply chains. The outcomes obtained will provide bureaucrats, decision makers, researchers, and industrialists in proposing and implementing measures for product development; devising effective marketing strategies, strategic planning of operations, effective policymaking and deliberating an ecological concern for the product considered.

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1 A detailed representation regarding the nation wise standings in surimi production is provided in Page number 1 and 2 in the Supplementary Material.

2 Fishing in the state of Maharashtra happens from the month of August till May. The months of June and July are barred for fishermen to promote breeding of fish species.
The research article is structured into the following sections: Sect. 2 provides an insight into the conventional LCA procedure used till date and explores the possibilities in enhancing the existing practice. Section 3 explains the results obtained and discusses the various outcomes. Section 4 concludes the research paper and possibilities for future work.

2 Materials and methods

2.1 Goal and scope definition

The LCA framework adopted in this study uses the ISO 14040 methodology that specifies the environmental assessment of the Indian surimi supply chain in the year 2018. This work adopts a functional unit (FU) of 1 kg frozen surimi block and evaluates the associated impacts till the processor gate. The results also estimate the amount of resources expended during each phase of the supply chain until distribution to a final surimi market (considered in this study).

The goal of this study is to address the Research Questions (RQs):

RQ1: Assess the environmental impacts of producing 1 kg frozen surimi block in the Indian case.
RQ2: Define and model supply chain scenarios following discussions with stakeholders and conclude the effect of impacts from supply chain moderations.
RQ3: Quantify environmental impacts during the end distribution of 1 kg frozen surimi and analyze its effect on the complete supply chain.

2.2 System boundary

The entire system boundary is divided into phases: the fishing phase, dock phase, and surimi processing. A unique representation of emissions and solid wastes generated across each process is presented in Fig. 1. This study focuses on Sassoon dock, located in the state of Maharashtra. The dock is sourced by 585 mechanized trawlers having varied engine capacities (i.e., 110–220 HP), overall lengths (OAL) (i.e., 15–19.9 m), and storage capacities (15–90 tons) (Kharatmol et al. 2018).

This study restricts fishing-related data to a single fishing boat type of 110 HP engine capacity, OAL of 15 m, and storage capacity of 40 tons. Fishing boats in India (focusing Mumbai city) lack an inbuilt refrigeration system and use crushed ice onboard for chilling the caught fish. Ice produced in processing plants is transported 32 km (approximately) to the dock, where it is crushed on-site and filled in boats manually. Upon return of fishing boats to the dock after fishing, fish is de-iced manually using water. Upon completion, the catch is unloaded manually, weighted, and transported to preprocessing centers located 2 km from the dock. The pre-processing centers perform the de-heading process.
operation separating the head and viscera (termed as RRM). The RRM generated is not considered in this study and is regarded as waste as it contributes to processing and distribution networks of its own. The absence of refrigerated trucks and the distant location of surimi processing plants require ice for maintaining fish quality. This requirement is contented by alternative ice producers located 32 km away from the dock. The de-headed fish is then sent to surimi processing plants located 34 km (approximately) from the dock where surimi is processed (refer to Fig. 3, Page number 3 in Supplementary Material for detailed process flow chart), stored, and sent for further distribution. The surimi processing plant (considered in this work) has an inbuilt production capacity of 24 MT/day, dispatching the final product (i.e., surimi) to countries such as Hong Kong, USA, Singapore, and Taiwan via sea route. Discussions with stakeholders further revealed that Bangkok was a prime customer for the consideration case organization. The frequency of dispatch however was unnoted due to issues of confidentiality in disclosure. Transportation, being an active contributor to GHG emissions (EPA 2020), requires quantifying assessments. This is proceeded by considering Bangkok as the target market and quantifying the associated impacts.

2.2.1 Assumptions and limitations

The assumptions and limitations deliberated in this work are as follows:

- Fish loss at the dock, maintenance data, end of life (EOL), and electric components used in fishing fleets are not considered (Das and Edwin 2016).
- The by-catch and wash water generated have been avoided due to the inability in quantification.
- Construction, maintenance, and end-of-life data of processing plants are avoided (Vazquez-Rowe et al. 2014; Avadi and Fréon 2013) owing to its negligible influence on overall impacts (Avadí et al. 2015).
- The onboard crew impact is not considered due to lack of precise data (Laso et al. 2018a, b).
- RRM generated from whole fish is not considered in the first part of the study and is regarded as waste in this work. This has been carried out as the generated RRM contributes to processing and distribution networks of its own that extends beyond the scope of this work. However, Sect. 3.6 tries to include the generated RRM into the LCA model to understand its effects on the environment.
- Refrigerant leakage at the surimi processing center and ice production plant have been assumed as 5% of the charge fed into the cooling system from Bovea et al. (2007) in all areas applicable in the LCA model.
- Marine-specific impact categories like biomass removal and seabed disturbance despite considerable occurrence in seafood literature (Woods et al. 2016; Ziegler et al. 2013) have been negated in this work but discussed briefly owing to its rising significance in Sect. 3.4.

2.3 Co-product allocation

Multispecies fishing in the Indian marine sector (Sathianandan 2013) requires allocating the derived environmental impacts among species required for surimi production and the caught by-catch. Both single- and multi-day trawlers in Mumbai vary in catch species owing to the varying fishing distance and depths reached. The mass allocation, economic allocation, and energy allocation methods are widely used for allocating impacts (Pelletier and Tyedmers 2011). Issues in data availability affected the exact quantification of fish energy/nutrition data for energy allocation (EA), making the adoption of EA challenging in this work. Mass allocation (MA) owed preference of the authors in comparison to economic allocation (EA) in this research work. This was primarily owing to its common usage in seafood LCAs (Laso et al. 2018a, b; Hognes et al. 2011) and also owing to the dynamic fish pricing existing across each supply chain stage, making EA adoption difficult. However, the adoption of EA in recent versions of Ecoinvent (Avadí et al. 2020) obligated the authors to study the influence of both allocation techniques on impact assessment outcomes considering the production of 1 kg frozen surimi blocks. Therefore, results obtained from both MA and EA are compared to check the similarity level between the results obtained in the upcoming section (for details, refer to Sect. 3.5).

Table 1 represents a detailed list of landings for 2018 by the 15 trawlers supplying to the case industry for producing surimi blocks. Besides, all ideals discussed in constructing the LCA model relate to the production of 1 kg frozen surimi block consisting of the weighted mean of all contributions to total landings per vessel (Avadí et al. 2018a, b). Co-product allocations using MA reveal 72% of the impact contribution, and EA denotes an increase in impact allocation to 81.21%. Allocations are proceeded considering the fish species used for surimi processing.

2.4 Inventory analysis

Data collection for inventory analysis involves primary data collected via semi-structured interviews and obtained industrial averages. In cases of unavailability of primary data, secondary data from literature and Ecoinvent 3.6 database are used. The cut-off Ecoinvent system model is used to analyze the environmental sustainability of the Indian surimi supply chain. Various input data mentioned in the inventory sheet along with a detailed split up of all processes are mentioned in Table 2. The data used in the LCA model are

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validated with the upstream members despite literary validation before constructing the LCA model. The data used in the LCA study includes all operational activities occurring in the supply chain from the production of ice for maintaining fish quality during fishing till the distribution of surimi to an international market. For better lucidity, the inventory data has been classified into pre-fishing, fishing, and post-fishing operations (Sultan et al., 2021). Pre-fishing operations comprise all operations that occur before fish catch from the construction of fishing boats and nets used for fishing, ice production and transportation. The fishing operation covers only the resources expended for the fish catch. Post-fishing operations include all activities after the landing of fish such as de-icing the iced fish, handling, processing (both pre-processing and post-processing), and distribution of the processed surimi to an international market.

Fishing vessel construction and net production details are taken as a proxy from Das and Edwin (2016). The lifetime of boats assumed in this work is 10 years. All transportation discussed use unrefrigerated trucks of capacity 16–32 MT, Euro 2. This selection is made considering the equivalence of Bharat stage II norms with Euro 2 engines used (Emission Standards 2018). Details of the ice production plant are obtained from technical reports provided by the manager of the ice producing plant. Operational data during fishing are gained from fishing boat captains (i.e., skippers). Fuel usage averages centered on annual fuel consumption are captured and used for further analysis in the LCA study. Activities like de-icing that require vast quantities of water are measured based on the left-over water in tanks used for the de-icing process. Operational information at the pre-processing plant and surimi processor are gathered from annual electricity bills and industrial averages quoted by the surimi processor. The electricity mix adopted in designing the ecological model is in specific to the state of Maharashtra, to achieve coherent results. Distances for tertiary transport are obtained from interactions carried out with respective stakeholders and online sources such as Google maps. Consultations also revealed that ship freight was the most sustainable mode of transportation for dispatching processed surimi to international markets with air freight distribution being a costly option. Hence, distribution via air freight has not been considered.

The inventory analysis clearly reveals that producing 1 kg of frozen surimi requires an average of 2.38 kg of whole fish. About 1.143 kg (average) of RRM produced from de-heading operation is exempted from this study. The remaining 1.237 kg of de-headed fish generated is used for surimi production. All values and distances considered in this study are average values.

### 2.5 Life cycle impact assessment

This research adopts the commonly used impact categories in fisheries LCA using ReCiPe 2016, adopting the midpoint technique (Huijbregts et al. 2016). Using the ReCiPe Midpoint technique, individual environmental problems are characterized by generating environmental flows assigned to an impact category (Huijbregts et al. 2016). The assessment includes 11 environmental impacts such as global warming potential (GWP), marine ecotoxicity potential (MEP), marine eutrophication (ME), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), fine particulate matter formation (FPMF), freshwater ecotoxicity (FWE), terrestrial acidification (TA), ozone formation human health (OFHH), ozone formation terrestrial ecosystems (OFTE), and fossil resource scarcity (FRS). Table 3 tabulates the impact wise categorization, potentials, and characterization factors used by ReCiPe in this manuscript.

The hierarchical perspective is retained owing to its scientific consensus considering the 100-year time frame and credibility of impact mechanisms (Huijbregts et al. 2016). For quantifying energy, the cumulative energy demand (CED) method is used. CED cumulates both non-renewable and renewable sources.

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### Table 1 Mass and economic allocation for fish caught by trawlers supplying to the surimi processing plant

| Species              | Common name      | Utilization       | Landings\(\*) (kg) | MA (%) | Value (INR*/kg) | EA (%) |
|----------------------|------------------|-------------------|---------------------|--------|----------------|--------|
| Priacanthus prolixus| Elongate bulleye | Surimi industry   | 19,345              | 11     | 224            | 13.77  |
| Johnieops vogleri    | Croaker          | Surimi industry   | 14,069.36           | 9      | 224            | 10.02  |
| Rastrelliger kanagurta| Indian mackerel  | Wholesale/Retail | 15,828.03           | 8      | 70             | 3.52   |
| Uroteuthis duvauceli | Indian squid     | Wholesale/Retail | 19,345.37           | 11     | 105            | 6.46   |
| Cynosoglossus macrostomus | Malabar sole | Surimi industry   | 5276.01             | 3      | 70             | 1.17   |
| N. randalli          | Threadfin bream  | Surimi industry   | 12,310.69           | 7      | 140            | 5.48   |
| Penaeid prawns       | Prawns           | Wholesale/Retail | 15,828.03           | 9      | 175            | 8.80   |
| Lepturacanthus savala| Small headed ribbon fish | Surimi industry | 22,862.71          | 13     | 122.5          | 8.90   |
| Otolithus cuvieri    | Tigertooth croaker| Surimi industry  | 42,208.08           | 24     | 280            | 37.57  |
| H. nehereus          | Bombay duck      | Surimi industry   | 8793.35             | 5      | 154            | 4.30   |

\*1 INR = 0.014 USD; as on 17/11/20; \*\*Landings represent averages
Table 2  Life cycle inventories for production of 1 kg frozen surimi in India

| System                  | Process                      | Inputs                        | Units | Real-time values | Data source |
|-------------------------|------------------------------|-------------------------------|-------|------------------|-------------|
| Pre-fishing operation   | Fishing boats                | Paints                        | kg    | 7.90E−03         | Dhas and Edwin 2016/Ecoinvent database V3.6 |
|                         |                              | Electricity                   | kWh   | 2.07E−03         |             |
|                         |                              | Welding electrodes            | kg    | 1.24E−04         |             |
|                         |                              | Fiber reinforced plastic      | kg    | 6.97E−02         |             |
|                         |                              | Gunmetal                      | kg    | 1.20E−03         |             |
|                         |                              | Hardwood log mix              | m³    | 1.24E−03         |             |
|                         |                              | Limestone                     | kg    | 1.80E−03         |             |
|                         |                              | Plywood                       | m³    | 4.52E−04         |             |
|                         |                              | Steel                         | kg    | 1.24E−02         |             |
| Fishing nets            |                              | Polyamide webbing material    | kg    | 3.64E−02         | Dhas and Edwin 2016/Ecoinvent database V3.6 |
|                         |                              | HDPE webbing material         | kg    | 8.09E−03         |             |
|                         |                              | Polypropylene rope            | kg    | 1.11E−02         |             |
|                         |                              | Lead sinker                   | kg    | 2.52E−02         |             |
|                         |                              | Brass                         | kg    | 2.64E−03         |             |
|                         |                              | Plastic rope                  | kg    | 8.09E−03         |             |
| Ice production unit 1   |                              | High speed diesel (HSD)       | kg    | 1.72E−02         | Personal communications with top-level managers/Technical reports/Ecoinvent database V3.6 |
|                         |                              | Electricity                   | kWh   | 8.30E−02         | Consumption bin cards available in the plant/ Ecoinvent database V3.6 |
|                         |                              | Water                         | kg    | 3.30E+01         | Personal communications with top-level managers/Technical reports/Ecoinvent database V3.6 |
|                         |                              | Refrigerant (R717)            | kg    | 1.60E−02         | Technical reports/Ecoinvent database V3.6 |
| Transport of ice blocks |                              | Diesel fuel                   | kg    | 1.39E−01         | Consumption averages from transporting agency/Ecoinvent database V3.6 in Open LCA |
| Fishing operation       | Fishing process              |                              |       |                  |             |
|                         |                              | Diesel                        | kg    | 9.36E−01         | Averages from fishing boat logbooks and fishers/Ecoinvent database V3.6 |
|                         |                              | Ice                           | kg    | 3.30E+01         |             |
| Post Fishing operation  | Handling at dock             |                              |       |                  |             |
|                         |                              | Water (for de-icing)          | kg    | 4.76E−01         | Data acquired from assessing water remains in water storage tanks |
|                         |                              | HDPE containers (high-density polyethylene) | kg | 1.07E+00 | Supplier technical documents |
|                         |                              | Wastewater/wash water         |       | Neglected        |             |
|                         |                              | Fish                          | kg    | 2.38E+00         |             |
| Transport to preprocessing center | Diesel fuel | kg | 1.50E−01 | Consumption averages from transporting agency |
| Preprocessing center    |                              |                              |       |                  |             |
|                         |                              | Electricity                   | kWh   | 7.29E−03         | Consumption bin cards available in the plant |
|                         |                              | Whole fish                    | kg    | 2.38E+00         |             |
|                         |                              | De-headed fish                | kg    | 1.24E+00         | Data acquired from plant managers |
|                         |                              | Waste water and blood         | Neglected |            |             |
| System                      | Process                        | Inputs                        | Units    | Real-time values | Data source                                                                 |
|-----------------------------|--------------------------------|-------------------------------|----------|-----------------|-------------------------------------------------------------------------------|
| Ice production unit 2       | Inputs                          | Solid waste (RRM)             | kg       | 1.14E+00        | Data acquired from plant managers                                             |
|                             | Inputs                          | High-speed diesel (HSD)       | kg       | 1.72E−02        | Personal communications with top-level managers/Technical reports/Ecoinvent database V3.6 |
|                             |                                | Electricity                   | kWh      | 8.30E−02        | Consumption bin cards available in the plant/Ecoinvent database V3.6          |
|                             |                                | Water                         | kg       | 3.30E+01        | Personal communications with top-level managers/Technical reports/Ecoinvent database V3.6 |
|                             | Outputs                         | Refrigerant (R717)            | kg       | 1.60E−02        | Technical reports/Ecoinvent database V3.6                                    |
| Transport of ice blocks     | Diesel fuel                     | Refrigerant leakage (from literature) | kg | 7.90E−04 | Bovea et al. (2007)                                                           |
| Transport to surimi plant   | Diesel fuel                     | Solid ice                     | kg       | 3.30E+01        | Personal communications with top-level managers                               |
| Surimi processing           | Inputs                          | Water                         | kg       | 1.85E+01        | Data acquired by averages from water flow meters                              |
|                             |                                | De-headed fish                | kg       | 1.24E+00        | Personal communications with managers                                         |
|                             |                                | Electricity                   | kWh      | 8.79E−02        | Consumption bin cards available in the plant/Ecoinvent database V3.6          |
|                             |                                | Refrigerant                   | kg       | 1.10E−01        | Values provided by plant HVAC engineer/Ecoinvent database V3.6               |
|                             |                                | Carton box packaging          | kg       | 1.21E−01        | Supplier technical documents/Ecoinvent database V3.6                         |
|                             |                                | HDPE crates                   | kg       | 7.66E−05        | Supplier technical documents/Ecoinvent database V3.6                         |
|                             |                                | Sodium tri polyphosphate      | kg       | 1.92E−03        | Technical documents from processor/Ecoinvent database V3.6                   |
|                             |                                | Sucrose                       | kg       | 0.79E+00        |                                                                                  |
|                             |                                | Salt for bleaching tank       | kg       | 1.92E−02        |                                                                                  |
| Dispatch                    | Surimi distribution             | Processed surimi              | kg       | 1.00E+00        | Personnel observations and processing plant averages/Ecoinvent database V3.6 |
|                             |                                | Wash water waste              | m³       | 3.71E+04        |                                                                                  |
|                             |                                | Processing waste              | kg       | 2.37E−01        |                                                                                  |
|                             |                                | Refiner waste                 | kg       | 3.00E−02        |                                                                                  |
|                             |                                | Refrigerant Leakage (from literature) | kg | 6.69E+00 | Ecoinvent database V3.6/Personnel communication with surimi processor/Distribution profiles provided by the supplier and Google maps |
|                             |                                | Transport, freight, lorry 16–32 metric ton, EURO2 | km | 18            | Ecoinvent database V3.6/Personnel communication with surimi processor/Distribution profiles provided by the supplier and Google maps |
|                             |                                | Transport, freight, sea, container ship with reefer, freezing | km | 4432       | Ecoinvent database V3.6/Sea route & distance (2018) [http://ports.com/sea-route/port-of-mumbai,india/port-of-hong-kong,hong-kong/](http://ports.com/sea-route/port-of-mumbai,india/port-of-hong-kong,hong-kong/) |
explaining the total energy flow based on lower heating values (Arvidsson and Svanström 2016; Farmery et al. 2014). The assessment is proceeded using the mass allocation technique firstly, and solutions obtained are compared with that retrieved by economic allocation using sensitivity analysis in Sect. 3.5.

2.6 Sensitivity analysis

Operations in the supply chain being time-dependent processes comprise inherent uncertainties. Uncertainties existing in the supply of fish (both catch and process lead time), climatic conditions, worker involvement, and transportation can influence the environment. Hence, the justification of this cause is made by carrying out a sensitivity analysis (SA). SA focuses on the supply chain domains that are prone to ambiguity, which are identified during the Goal and Scope of the study (refer to Sect. 2.1). Fuel consumption during fishing and transportation distances is subject to SA to conclude the effectual influence on the environment.

2.7 Research overview

This study involves fishing data obtained from fishing boats, pre-processing centers, and chosen case organization located in Maharashtra, India (18.9128° N, 72.8257° E). Primary data used for scheming the process flow of Indian surimi production were collected from onsite visits made to the fishing dock (i.e., Sassoon dock) and leading surimi processor (chosen case organization for this study). Figure 2 signifies the research methodology adopted in the current work. The attributional LCA approach adopted in this work (Brander et al. 2008) makes use of a combination of primary data and secondary data. Open LCA software V1.10 is used for assessing the environmental impacts for producing frozen surimi in India.

Three supply chain alternatives consisting of the Current State, Scenario 1, and Scenario 2 are considered with varied level of improvements to be implemented (refer to Fig. 3). The improvements discussed under each supply chain alternative try to revamp the supply chain operating structure. Improvements in Scenario 1 involves replacing of individual ice processors located at different distances, serving both processing and pre-processing plants with a single ice processing plant. An added improvement involves the shifting of pre-processing operation into the surimi processing plant. All these developments espouse the partial localization of operations with reduced transportation in the supply chain. Improvements in Scenario 2 involves all improvements identical from Scenario 1 followed by the deep localization of supply chain operations by decreasing transportation distances and reducing dependence on tertiary logistics. The notion of deep localization in this study involves localizing the processing plants and ice producers within a zone near the dock. The distances used for

| Impact assessed under this work | Impact category | Indicator | Characterization factor | Abbreviation used in this work | Units |
|----------------------------------|----------------|----------|------------------------|------------------|-------|
| Global warming potential         | Climate change | Infrared radiative forcing increase | Global warming potential | GWP | kg CO₂ to air |
| Human carcinogenic toxicity      | Human toxicity cancer | Risk increase of cancer disease incidence | Human toxicity potential | HCT | kg 1,4- DCB to urban air |
| Human non carcinogenic toxicity | Human toxicity cancer | Risk increase of non-cancer disease incidence | Human toxicity potential | HNCT | kg 1,4- DCB to urban air |
| Fossil resource scarcity        | Fossil resource scarcity | Upper heating value | Fossil fuel potential | FRS | kg oil |
| Ozone formation terrestrial ecosystems | Ozone depletion | Stratospheric ozone decrease | Ozone depletion potential | OFTE | kg CFC-11 to air |
| Ozone formation human health    | Ozone depletion | Stratospheric ozone decrease | Ozone depletion potential | OFHH | kg CFC-11 to air |
| Fine particulate matter formation | Fine particulate matter formation | PM 2.5 population intake increase | Particulate matter formation potential | FPMF | kg PM 2.5 to air |
| Freshwater ecotoxicity           | Freshwater ecotoxicity | Hazard weighted increase in fresh waters | Freshwater ecotoxicity potential | FWE | kg 1,4 DCB to fresh water |
| Terrestrial acidification        | Terrestrial acidification | Proton increase in natural soils | Terrestrial acidification potential | TA | kg 1,4 DCB to industrial soil |
| Marine ecotoxicity potential     | Marine ecotoxicity | Hazard weighted increase in marine water | Marine ecotoxicity potential | MEP | kg 1,4 DCB to marine water |
modeling the localization scenarios were provided by the case industry considered in this work.

3 Results and discussion

3.1 Impact assessment

A multi-perspective approach embraced in this work aims to quantify (i) environmental hotspots till the production of surimi at the processor gate and (ii) environmental hotspots of surimi production when distribution to an end market is included. The impact evaluation has been carried out individually to address the lacuna in each phase and identify the chief impact contributors.

Ecological impacts signified in Fig. 4 reveal impact share till the processor gate (i.e., surimi production). A stage-wise impact valuation reveals that boat construction shows visible impacts in FWE and ME with minimal overall impacts. This outcome coheres with the statements of Avadí et al. (2018a, b) and Ziegler et al. (2018). The effect of paints used in fishing boats is evident in influencing ME (30%), HNCT (8%), FWE (5%), and HCT (4%). Emissions emitted from paints used on fishing boats, despite its low contribution in

Fig. 2 Research methodology for LCA of Indian surimi supply chain
value, is also found to have a significant impact on toxicity. This derivation is found to be in coherence with the results obtained from Laso et al. (2018a, b) who stated similar narrations. The fishing phase has the maximum environmental impact among the environmental indicators assessed in this work (averaging 74%). Additives used in surimi processing showed minimal impacts (around 2%) influencing HCT and HNCT respectively. Processing and packaging have also minimalistic impacts of 2% in OFHH, OFTE > 2% in HCT and have an insignificant impact on TA, FRS, HNCT, and GWP. A detailed depiction of quantification of assessed impacts under different surimi production phases is further discussed (for details, refer to Table 1 in Supplementary Material), satisfying RQ1 of this work. Overall, it is found that a dominance in impact is evident in FPMF, FRS, and GWP. All evaluated impacts have been detailed in the upcoming sections (Sect. 3.1.1-Sect. 3.1.7).

3.1.1 Global warming potential

GWP, primarily being a tool for measuring GHG emissions (EPA 2017), contributes 1.122 kg CO₂-equivalent/kg of fish caught. These values are found to be in coherence with emission ranges of 0.59–1.18 kg CO₂-equivalent/kg fish caught in India (Vivekanandan et al. 2013). Comparing the obtained value with international averages, the obtained emission intensity is much below the global fisheries average of 2.2 kg CO₂-equivalent/kg fish (Parker et al. 2018). This might be due to the calculation of the global fisheries values from industrial fleets with advanced technology, varying catch distances and different functions available on fishing boats for the comfort of the fishermen. In contrast, the values obtained in the current study were from small-sized boats with less storage capacity which are owned and operated by marginal fishermen. Carbon emission and fuel consumption being inter-reliant depend on many factors such as the size of the vessel, age and condition of the fleet, engine power, vessel speed, and weather conditions during travel (Driscoll and Tyedmers 2010; Schau et al. 2009).

Surimi production phases show minimal impacts for “boat construction” (0.0772 kg CO₂-equivalent/kg of surimi produced), “processing” (0.969 kg CO₂-equivalent/kg of surimi produced), and “others” (0.146 kg CO₂-equivalent/kg of surimi produced). The significant flow contributions to this impact category were found to be from carbon dioxide (< 90%) emitted from fossil fuels consumed during the production. Diesel consumption (~ 50%), electricity production (~ 17.61%), and ammonia production (~ 12.88%) influence the maximum impacts under the GWP impact category.

3.1.2 Human toxicity (HCT and HNCT)

Human toxicity impacts human health with emissions discharged through the air, water, or land. Human toxicity in this section comprises both HNCT and HCT owing to its similarity in the depiction of 1,4 dichlorobenzene (DCB). Both HNCT and HCT contribute to emissions produced from toxic metals during the production of copper, cast iron, and steel. These significantly occur during fishing, and mere occurrences are evident from boat construction, processing,
and packaging operations in the Indian surimi supply chain. Impacts from “boat construction” amount to 0.352 kg 1,4-DCB (constituting ~14%), followed by “fishing” amounting to 2.02 kg 1,4-DCB (constituting ~56%), processing 0.322 kg 1,4-DCB (constituting ~15%), and “other” impacts quantifying 0.23 kg 1,4-DCB (constituting ~15%).

Significant contribution under HCT comes from “fishing” (valuing 5.62E−02 kg 1,4-DCB and constituting ~52%) followed by “processing operations” (valuing 2.50E−02 kg 1,4-DCB and constituting ~22%). All remaining phases are found to have minimal overall impacts. Despite individual stakes, the overall influence of HCT and HNCT among the assessed ecological impacts is relatively low with each impact group contributing a mere 3% and 2%, respectively. A significant portion of pollutant flow in both HCT and HNCT are from chromium, nickel (in HCT), zinc, and barium (in HNCT), discharged into water systems. The availability of nickel below the acceptable range of 10E−4 assured the reduced risk of carcinogenicity (Satapathy and Panda 2017).

3.1.3 Fossil resource scarcity

FRS signifies the amount of fossil fuels expended in the production of 1 kg surimi. Requiring 0.937 kg oil equivalent per kg of surimi produced, a significant percentage of contributions from fossil resource scarcity arises from the fuel production (69%), coal production (15%), and nylon 6–6 production glass filled (12%) with minimalistic contributions from gas production, ethylene, etc. FRS projects an overall impact of 19% among the analyzed environmental impacts.

Operation wise impact assessment reveal a significant share of impact from fuel consuming operations such as “fishing” quantifying 0.712 kg oil equivalent (constituting ~76%) and “other operations” quantifying 0.159 kg oil equivalent (constituting ~17%) that include terrestrial transportations. Comparatively negligible impacts are visible from “boat construction” quantifying 0.00937 kg oil equivalent (constituting ~1%) and “processing” valuing 0.0562 kg oil equivalent (constituting ~6%).

3.1.4 Marine ecotoxicity potential

MEP corresponds to the unnecessary loading of the marine environment by excess nutrients such as nitrogen or phosphorus, leading to the overgrowth of plants and algae in marine ecology. MEP leads to algal blooms, oxygen depletion in lower water areas, and mortality of fishes that live in deep waters. Release of nitrate into water and soil is found to be the single largest contributor to MEP. The sources are chiefly from “fishing” quantifying 0.249 kg 1,4 DCB (constituting ~84.98%), marginal impacts from “boat construction” measuring 0.0205 kg 1,4 DCB (constituting ~6.99%), and “others” measuring 0.0234 kg 1,4 DCB (constituting ~7.98%). With an overall share of 12%, MEP poses a value of 0.293 kg 1,4 DCB per kg of surimi produced.
3.1.5 Ozone formation (OFTE and OFHH)

The impact of ozone formation, despite its categorization into human health and terrestrial ecotoxicity, is influenced by nitrogen oxides and NMVOC damaging the terrestrial ecosystem. This section covers the effects of both OFTE and OFHH owing to their likeliness in representation (i.e., kg NOx equivalent). Both OFTE and OFHH contribute 6% and 5% individually, considering the overall environmental impacts analyzed in this work.

A phase-wise impact assessment in both OFTE and OFHH signifies similarity in individual emissions. OFTE quantifies 5.66E−03 kg NOx equivalent per kg of surimi produced, whereas OFHH values 5.30E−03 kg NOx equivalent per kg of surimi produced. Phase-wise impact share in both impact categories are similar with sources primarily being from “fishing” (~ 86.04%) followed by “boat construction” (~ 8%) and minimal impact shares from “processing” (~ 0.5%) and “other processes” (~ 5.4%). With electricity generation (~ 11.8%), transport (~ 10%), nylon 6–6 production (~ 9.2%), and diesel consumed (~ 5.8%) playing dominant roles. NOx has the maximum emissions to the environment (< 70%), with significant shares from NMVOC. The contributions of methane, ethane, and pentane are found to be in negligible amounts in both OFTE and OFHH.

3.1.6 Fine particulate matter formation

FPMF contributes 5.63E−03 kg PM2.5 equivalent per kg of surimi produced, posing an overall impact of 22%. Electricity production (28.31%), diesel burned (18.14%), nylon 6–6 production glass filled (6.92%), copper production (7.29%), and ammonia production (5.05%) play dominant roles in impacts with negligible shares from transportation and other minor categorical impacts. Phase-wise impact scrutiny reveals a significant share of impacts from “fishing” (~ 93.25%) and minimal impacts from “other processes” (~ 2%) in the supply chain.

3.1.7 Other impact categories

Beyond the above mentioned impacts, three other impacts, namely, freshwater ecotoxicity (FWE), terrestrial acidification (TA), and marine eutrophication (ME) are also to found to have trivial shares in the production of frozen surimi. FWE poses an overall impact of 13% with individual impact contributions of 2.25E−01 kg 1,4-DCB per kg of surimi produced. TA contributes 1.26E−02 kg SO2 in the production of 1 kg surimi, having an overall impact of 3%. Significant environmental flows are observed from sulfur dioxide (78%) and nitrogen dioxide (20%) with minimal contributions from ammonia and other forms of sulfur oxides present. The ME is observed to have an overall impact share of 1% with an individual impact contribution of 3.57E−04 kg N equivalent per kg of surimi produced.

3.2 Comparison of supply chain alternatives

Each supply chain alternative discussed (i.e., Scenario 1 and Scenario 2) introduces a development from its baseline state (i.e., existing state of surimi supply chain configuration). Outcomes from this research denote significant improvements under both partial localized scenario (i.e., Scenario 1) and completely localized scenario (i.e., Scenario 2) (For details, Refer Table 1 in Supplementary Material).

Scenario 1 signifies improvements in FRS (9%), HCT (7%), GWP (6%), FPMF (%6%), OFTE (6%), OFHH (6%) TA (4%) ME (3%), HNCT (2%), MEP (2%), and FWE (1%). Inferring the various states analyzed, significant improvements are evident in Scenario 2 that involve the efficient structuring of the supply chain by deep localizing supply chain operations. Scenario 2 showcases improvements in FRS (20.49%), HCT (16.35%), GWP (15.80%), FPMF (11.47%), OFTE (14%), and OFHH (14.71%) followed by other impact categories sharing minimal impacts. The supply chain enhancements in Scenario 2 positively control the flows of carbon dioxide in GWP; particulates < 2.5 μm, sulfur dioxide, and nitrogen oxides in FPMF; production of coal and oil in FRS; zinc, nickel, and copper in FWE; chromium 6 in HCT; zinc, mercury, and thallium in HNCT; zinc, silver, and copper in ME; and nitrogen oxides, and NMVOC in OFTE in contrary to other alternatives discussed, hence being comparatively eco-friendly. Overall, both Scenario 1 and Scenario 2 showcase an overall improvement averaging 5.04% and 11.24%, respectively. Figure 5 signifies the percentage variation occurring across the analyzed scenarios in comparison with the current state. The outcomes obtained hence satisfy RQ2 of this study.

3.3 Impact assessment including downstream distribution

The values derived from the inclusion of sea freight distribution in the developed LCA model (refer to Table 1 in Supplementary Material) reveal that downstream distribution plays a pivotal role in assessing the environmental impacts. Distribution constitutes an overall share of 34% on the assessed environmental impacts. Besides the mode of transport adopted, speed and transportation time also play the deciding roles in influencing the level of impacts (Hognes et al. 2011). Figure 6 signifies the overall ecological impact, revealing contributions from distribution to the end market being 100% in ME, around 50% in TA, > 74% in OFHH and OFTE.

A scenario-based comparison reveals similar deliverables as obtained previously (i.e., Sect. 3.2). The inclusion
Considering the marine impacts, current day LCA modules still lack a structured assessment of the naturally occurring biotic resources (European Commission 2017). Research in this particular domain is mainly found to be classified into impacts from seabed damage and impacts from overfishing. Appreciated works by Ziegler et al. (2003) discussed the area of seafloor swept by bottom trawling, quantifying the effectual impact on the benthic ecology. Recent works involve the contribution of Woods and Verones (2019) who presented an approach for quantifying species wise seabed damage impacts from abrasion and extraction processes in terms of time-integrated relative species loss. Research on effect of overfishing is witnessed in valued works done by Emanuelsson et al. (2014) who proposed the lost potential yield (LPY) as a midpoint impact category quantifying overfishing in European fish stocks. The constructive nature of the technique adopted is its usability in conditions of reduced data availability.

However, considering the wide amount of data required for this analysis, the authors feel the adoption of biotic natural resources (BNR) in estimating the amount of time required for the rejuvenation of the harvested fish stock to be the most apt method considering the current situation of data restrain. This assessment positively assists in scheming the amount of damage caused while fishing a particular fish stock. Derived from Langlois et al. (2014) and used by Avadi et al. (2014), BNR both at the species level ($I_{BNR, sp}$) and ecosystem level ($I_{BNR, eco}$) are found. This work was further improved by Hélias et al. (2018) to evaluate the effects of multiple fish species. This involved characterization factors (CF) to quantify biotic resource impacts by converting the mass of fish caught into depletion stock fraction (DSF) allowing multi fishery comparison. Using easily retrievable information (such as catches, current stock biomass, and maximum intrinsic rate of population increase), CFs are calculated using spatial and taxonomic aggregations.

The methods discussed, however, get difficult to be adapted in the Indian stance mainly owing to naïve information capturing techniques available in fishing among marginal fishermen making data limitation to be the prime reason averting adoption. Supplementing it, the biotic resource use (BRU) is found to assess the primary productivity consumed by an organism at a given trophic level (TL). Despite the shorthand calculation being a comparatively easier alternative, localized specifics and incomplete information impede the quantification of the species used in this study. Another reason for overlooking these impacts is owing to the limitation...
3.5 Comparison of results by mass allocation and economic allocation

Adopting the fundamentals laid by ISO 14044, the appropriate allocation technique (i.e., mass allocation or economic allocation) has to be selected. A sensitivity analysis of the different supply chain alternatives is carried out for two allocation techniques to estimate the variations in results along selected environmental impacts as suggested in the literature (Ayer et al. 2007). Shifting the allocation technique from mass to economic signified a visible increase in impact categories assessed (ranging 4–12.21%) with a decrease in TA (−5.5%) and FPMF (−1.3%) values. The outcome further adheres with the conclusions of Svanes et al. (2011), who affirmed an increase in ecological impacts after economic allocation. A detailed response of the varying levels of impacts is represented in Fig. 8. Despite variations witnessed, the authors feel the results obtained to be within the limits of coherence for economic and mass allocations as obtained by Eyjólfsdóttir et al. (2003). Hence, the MA is considered as preferred allocation technique in the current study owing to the dynamic pricing existing between stakeholders with price variations being reliant on the supply chain member handling.

Fig. 5 Percentage improvement in scenarios considered

Fig. 6 Relative environmental impacts considering distribution

Marine Eutrophication
Terrestrial Acidification
Freshwater Ecotoxicity
Fine Particulate Matter Formation
Ozone Formation Human Health
Ozone Formation Terrestrial Ecosystems
Marine Ecotoxicity Potential
Fossil Resource Scarcity
Human Non carcinogenic Toxicity
Human Carcinogenic Toxicity
Global Warming Potential

Fishing Activity  Surimi processing  Distribution
purchase, volume purchase, the demand of the product, and season of catch.

### 3.6 Analyzing case alternative

This section evaluates the two diverse facets of this work: (i) to study the disparity in environmental impacts when the generated RRM (previously regarded as waste) is included in the LCA model and (ii) to analyze the incurred GWP expended for dispatching 1 kg surimi to Bangkok (via sea freight) as insisted by the case organization.

The RRM generated during surimi processing voluntarily avoided earlier (as it is beyond the scope of this current study and owing to its limited valorization in the case industry) is assumed to be included in the LCA model. Inclusion of RRM disclosed a large increase in impacts of the order HNCT (46%), GWP (60%), FRS (108%), MEP (46%), FWE (41%), HCT (66%), TA (43%), FPMF (58%), OFTE (80%), OFHH (80%), and ME (41%). It is necessary to make note that the mere inclusion of any waste into the LCA model increases the impacts. Efficient valorization of generated RRM would

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**Fig. 7** Improvement in surimi distribution under varying scenarios

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**Fig. 8** Variation (%) between mass and economic allocations
bring a significant reduction in impacts, increasing value addition (Laso et al. 2018a, b). This, in turn, can pave ways to prosper developing and existing markets (Pajula et al. 2017).

To enumerate the environmental impact incurred for dispatching 1 kg surimi to Bangkok (via sea freight), a focus on GWP is extended (Fuglestvedt et al. 2010) considering different scenarios. Figure 9 provides an operation-wise representation of the impacts of constituting GWP. Results obtained acknowledge the fact of reduced emissions from distribution by sea (McCollum et al. 2010).

### 3.7 Sensitivity analysis

To understand the level of variation in impacts, sensitivity analysis (SA) was conducted by varying fuel consumed during fishing by ± 5% and tertiary transportation distances by ± 10%. The results show that data uncertainty has a minimal impact on the majority of the indicators. Reduced disparities are visible in the outcomes in fishing, with FRS and GWP showing 3% and 2% variations in values in both cases. A variation of 1% is observed in TA, FPMF, OFTE, and OFHH, with the rest impact categories having nil variations. The effect of uncertainty in transportation is high in ME (11%) with all other impacts showing a 1% variation.

### 3.8 Economic analysis

Adopting an alternative supply chain structure is reliant on cost and profits at the processor level. Hence, an economic analysis has been carried out considering the various charges at Mumbai. Table 4 mentions cost and profit estimates to produce 1 kg surimi from 2.38 kg of raw fish. The prices, however, mentioned, are prone to seasons and place of study adopted. The analysis reveals an economic advantage in Scenario 2, further strengthening the adoption of this sustainable supply chain alternative. An added attempt is made in quantifying monetary gains using the CED values obtained across each supply

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**Table 4 Economic analysis**

| Factor                      | Unit cost per kg (INR) | Total cost per kg (INR) |
|-----------------------------|------------------------|------------------------|
|                             | Current state | Scenario 1 | Scenario 2 | Scenario 2 |
| Raw fish                    | 40 (avg)        | 95.2       | 95.2       | 95.2        |
| Dock charges                | 2               | 4.76       | 4.76       | 4.76        |
| Preprocessing charges       | 20              | 47.6       | 0          | 0           |
| Logistics cost              | 13              | 30.94      | 26.18      | 4.76        |
| Surimi processing (fixed cost) | 98           | 98         | 98         | 98          |
| Cumulative Cost             | -               | 276.5      | 224.14     | 202.72      |
| MRP (global average)*       | 756.7          | 756.7      | 756.7      | 756.7       |
| Income per kg of surimi (INR) | -             | 480.2      | 532.56     | 553.98      |
| Savings/kg                  | -               | -          | 52.36      | 73.78       |

*International price (Source: Tridge 2018). Price conversion 1 USD = 70 INR*
chain scenario. This is done to cost the direct and indirect energy used across the product’s lifecycle from fishing to the processor gate. CED values obtained in the current state, Scenario 1 and Scenario 2, were 64.6 MJ, 62.1 MJ, and 58.4 MJ, respectively, per kg of surimi produced. With 1 kWh costing INR 5/kWh (approximately), the analysis reveals that Scenario 1 and Scenario 2 produce economic savings of 3.86% and 5.95%, respectively. The values conclude the costing efficiency of the scenarios considered considering the savings in resources and money expended.

4 Conclusion and recommendation

The main objective of the current work is to assess the environmental impact generated from the production of 1 kg frozen surimi in India. Results also denote that supply chain alternatives can reduce environmental emissions. Outcomes indicate Scenario 2 to be the most sustainable alternative for the existing surimi supply chain. Translating environmental improvements into fiscal gains proves satisfactory considering the increased economic gains obtained from enhancements. Some significant conclusions derived from this study are as follows:

- Midpoint assessment till processor gate reveals maximum impact from the fishing phase (around 74%). However, the share of impacts from the fishing phase reduces to around 54% when market distribution is considered.
- Significant environmental improvements in the range of 10–15% from the baseline values are evident in FRS, HCT, and GWP from the supply chain scenarios considered.
- Results derived from both mass allocation and economic allocation are compared using sensitivity analysis to reveal the existence of coherency between results.
- GWP computations across different supply chain scenarios considered (including ship freight) reveals impact reduction per kg of surimi produced from 4.673 kg CO₂ equivalent/kg to 4.063 kg CO₂ equivalent/kg.
- Sensitivity analysis reveals minimal impacts (around 3%) in terms of GWP reduction and > 1% in other impacts assessed.
- Economic analysis indicates savings of 9.83% and 13.31% in Scenario 1 and Scenario 2, in contrast to the existing state of supply chain. Analysis further reveals energy savings (i.e., in terms of monetary value) of 3.86% and 5.95% per kg of surimi block across the considered life cycle of the product.

Although this research evaluates the less focused Indian surimi scenario, valuable research can still be carried out in analyzing the effect of fishing on the Indian marine ecosystem and biotic resources. The outcomes obtained can assist in quantification and transformation to a sustainable Indian marine bio-ecosystem. Further work in terms of assessing the supply chain system-wide cost that includes the amortized fixed cost for adopting the suitable supply chain alternatives can positively aid in adopting these alternatives in the Indian scenario. Executing supply chain reforms can influence local employability, necessitating capturing the social sustainability involved by conducting Social LCA (SLCA) studies. Significant technology use changes can also play eco-dominant roles that need to be ventured for imparting a responsibly sustainable surimi supply chain in India. Another area that can be explored relates to the replacement of conventional refrigerants like NH₃ (commonly used industrial refrigerant in India) with refrigerants such as CO₂, owing to its increased efficiency and climate-friendly nature.

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