DOI: 10.18462/iir.gl2022.0190

# Assessment of benefits of employing natural refrigerants in seafood cold chain in India

**Santosh Kumar SAINI*[(a)], Mani Sankar DASGUPTA[(a)], Kristina N. WIDELL[(b)] , Souvik BHATTACHARYYA[(a)]**

[(a)] Department of Mechanical Engineering, BITS Pilani
Pilani, 333031, India,
[(b)] SINTEF Ocean, NO-7464, Trondheim, Norway
*Corresponding author: santoshsaini633@gmail.com

## ABSTRACT

In this paper we present a comprehensive assessment of benefits from adoption of suitable natural refrigerants at various stages of seafood cold chain in Indian scenario. This includes cooling demands during fish harvesting, transport of fresh catch, sorting and processing, and long-time storage. For each stage, the cooling demands are estimated and simple refrigeration cycle configurations are simulated to estimate the annual energy consumption and total equivalent warming impact for suitable natural refrigerants from among $NH_3$, $CO_2$, and hydrocarbons such as R170, R290, and R1270. The same is compared with synthetic refrigerants presently used for such application like R22, R134a and R404A etc. Field data from a surimi supply chain in west coastal region and shrimp supply chain in east coastal region of India are used for the study. The results highlight the potential benefits from use of natural refrigerants in seafood sector. Further, the various barriers in terms of technological, economic and policy related are highlighted.

Keywords: Industrial refrigeration, Low GWP, Seafood cold chain, NH3-CO2 cascade, Natural refrigerants, Energy efficiency.

## 1. INTRODUCTION

India is self-reliant on food and is also a prominent exporter. However, India experiences an estimated 40% food loss and/or waste (NAAS, 2019), most of that during post-harvest processing, transport and storage. The food supply chains have a huge potential of improvements in India with appropriate cold chain integration. Food processing is recognized as a priority sector by the Government of India (Rais et al., 2014), aiming technological advancements in handling and quality assurance throughout the whole supply chain. India has large coastline of over 7500 km length and inland water resources of 7 million hectares, naturally it is a major seafood and aquaculture producer and exporter. The major concern when dealing with the seafood is large post-harvest losses due to its highly perishable nature. Many factors attribute to the losses, but inadequate cooling and interrupted cold chains lead to maximum losses.

Refrigeration and cold chain demands are increasing across the globe but are more prominent in developing countries like India to meet the ever increasing demand of food, comfort and medicines. Seafood and aquaculture supply chains have large refrigeration demands at various stages from harvesting to consumption and a large amount of energy is consumed to cater to these refrigeration needs. Refrigerants that are commonly employed in seafood cold chain in India include R22, R404A, R134a, R410A, R407C and $NH_3$, some of which have high global warming potential (GWP) and led to high greenhouse gas emissions (Kumar et al., 2018). The Kigali amendment of the Montreal Protocol is regulating the use of high GWP refrigerants worldwide and aims to reduce the production and consumption of the same by 80% over the next 30 years. The pathway to implement this regulation is to reduce dependency on high GWP refrigerants and adoption of low GWP alternatives with energy efficient technologies. India demonstrated leadership in 2019, by being one of the first countries to launch the India cooling action plan to regulate refrigerant use and enhance cooling efficiency. In September 2021, India ratified the Kigali amendment and is working towards development of a national strategy in the next year to oversee phase down of HFCs in consultation with the stakeholders (Chatterjee, 2022). Across the world, there is serious demand for energy-efficient and environmental-friendly solutions to meet the increasing refrigeration requirements. Consequently, use of natural refrigerants have undergone a revival, especially various hydrocarbons, $NH_3$ and $CO_2$ usages for specific applications. Therefore, refrigeration systems with improved energy efficiency and using natural refrigerants is considered to be sustainable solution for India.

This study is intended to comprehensively explore various benefits and challenges associated with adoption of natural refrigerants like $CO_2$, $NH_3$ and hydrocarbons R170, R290 and R1270 with focus on refrigeration demands at various stages of seafood cold chains in India. The study is based on field visits, and surveys conducted in India at Mumbai for surimi, Kolkata for shrimp, and Udupi for rest raw material. We analyzed three scenarios of refrigerant mix use in India and simple refrigeration cycle-configurations are simulated to estimate the energetic and environmental performances for these scenarios.

## 2. MATERIALS AND METHODS

The absence of requisite cold chain infrastructure in the supply side for the Indian seafood industry is identified as one of the main barriers for growth (Raghuram & Asopa, 2008). A report by the national center for cold chain development (NCCD, 2015) assessed the gaps in demand and available capacity of the pack-house, cold storage (bulk and hub) and reefer transport at 97%, 9% and 85% respectively. Sharma et al. (2018) studied the supply chain and marketing infrastructure for marine fisheries in the state of Gujrat in India and concluded that very less importance is given to post harvest infrastructure in marine sector which resulted in unhygienic work condition leading to contamination of raw material. They also found that due to lack of infrastructure, the retail market operated under open sky and due to less availability of ice and improper handling, the quality of fish deteriorates. A few other studies of course pointed out distinct bias of Indian consumers towards fresh catch and general aversion towards iced vending, which is perceived to be old catch. Dasgupta et al., (2019) discussed the stages involved in the complete surimi supply chain in India, the temperature requirements and temperature abuses in the cold chain. Further, the authors suggested various strategies along with need of advanced refrigeration systems that may be deployed to make cold chain more robust and by that process, avoiding quality degradation of seafood. In a simulation based study of the downstream operations of various stages of surimi supply chain in India, Sultan et al., (2021) concluded that the current Indian surimi supply chain is highly fragmented and needs a vertical integration to make it sustainable and responsive. They investigated three scenarios and concluded that a total integration can reduce 74.5% in lead time, 79.7% in emissions and 82.0% in energy consumption involved in various processes.

Depending upon the end product and processing, the cooling demand in seafood supply chain varies. The frozen seafood supply chain, which includes shrimp/prawns, fillets or minced meat, have prominent pre-processing requirements like heading, gutting, skinning mostly requiring human intervention before processing and deep freezing. A typical surimi and shrimp supply chain followed in India are presented in the subsequent sections.

### 2.1. Surimi supply chain

Among the processed seafood exported from India, surimi has a significant share with good potential for growth. It is obtained through mechanically mincing and stabilizing fish meat. Surimi industries generally utilizes the species which have otherwise low commercial value and is mostly from catch in sea. In year 2020-21, export share of surimi out of total seafood was about 13% (142975 MT) by volume and contributed to export earnings of 378.3 million USD (MPEDA, 2021). Most of the surimi processing plants are located on the western coast of India in the state of Gujrat and Maharashtra. Surimi production yields about 25% of the raw material (Park, 2005), therefore about 571900 MT of raw material is assumed to be required annually to produce 142975 MT of surimi. India has a fishing ban of two months every year during monsoon period to allow fish to bread and repopulate the water. Thus, fish harvesting is done for about 304 days in a year. Therefore, per day approximate production of surimi from India is 470 MT from a total 1880 MT raw material. The supply side of surimi cold chain is pictorially represented in Figure 1. It has large cooling demands at various temperatures and have a lot of scope of improvement that can contribute to overall quality improvement as well as yield. It has five major stages: a) Fish harvesting, b) Fish handling and pre-processing, c) Transport to processing plants, d) Processing in factory and e) Storage.

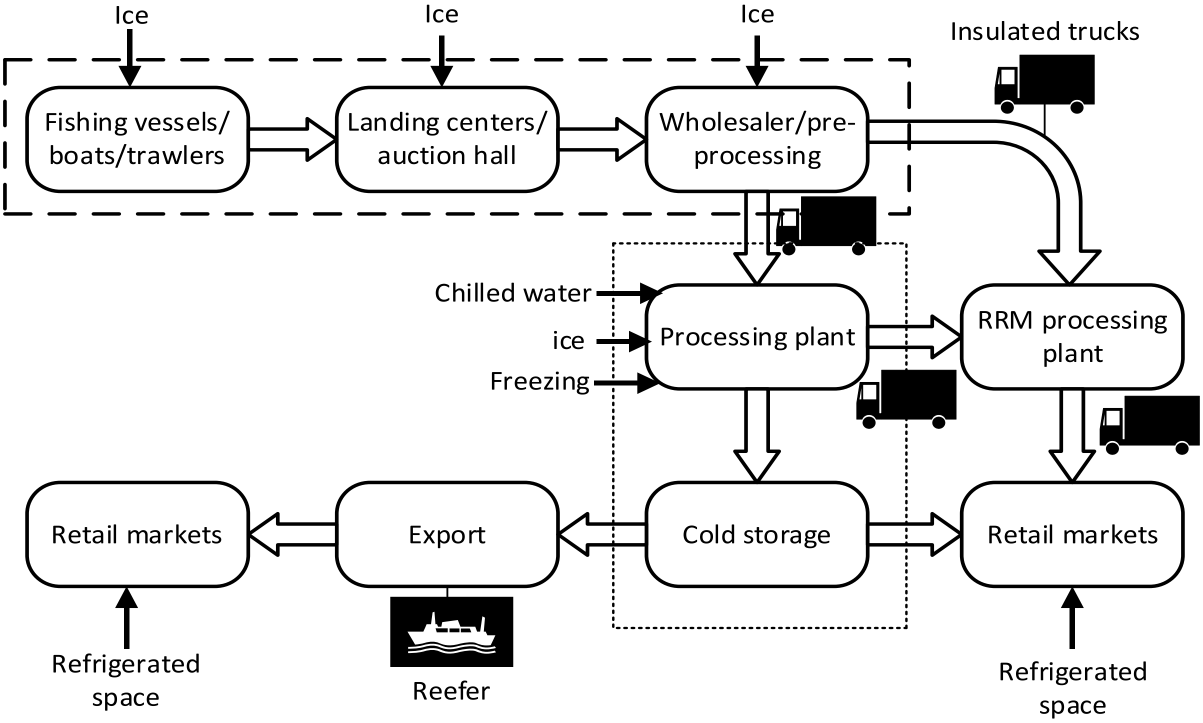


**Figure 1: Various stages in surimi supply chain**

### 2.1.1. Fish harvesting

Purse seining and motorized small fishing boats dominant the fish harvesting scenario in Indian west coast. Immediately after harvesting, on-board preservation is essential because once the freshness and nutritional value of fish is lost, it cannot be recovered during the processing stages. The small boats generally carry crushed ice from shore, which is stored in the insulated compartments within the boat. Fresh catch after sorting is kept sandwiched between layers of ice. The melting ice wets the fish and is an effective medium to carry away heat and preserve the fish near 0 ºC. Ice consumed is in a ratio of 1:1 to 2:1 (Sultan et al., 2021) depends upon number of days and harvesting season. In the analysis, the estimated average ice consumption per day is taken as 2:1 of fish catch which is about 3760 MT.

### 2.1.2. Fish handling at landing centres

Due to the fragmented nature of supply chain, the catch changes hand at landing site requiring de-icing and weighing to settle payments. This practice leads to exposure of fish to ambient temperature and is identified as a serious temperature breach and as a prominent source of pilferage and quality loss in the overall cold chain (Dasgupta et al., 2019). During our surveys, we also observed manual sorting in open space without any cooling arrangement at the landing sites. Sultan et al., (2021) observed that this phase has about 8 hours 37 minutes of non-value added time is avoidable with technology usage. The weighed sorted and pre-processed fish is then re-iced at landing centers. About 200 kg of ice is used per ton of fish at the processing centers to maintain the low temperature. The total use of ice at this stage is thus assessed as 376 MT per day.

### 2.1.3. Transportation to processing plant

Insulated trucks, pick-ups or even open trucks are used to carry crates filed with iced fish to the processing plants. Additional quantity of ice is used for transportation and the quantity varies with travel time and ambient temperature. For transportation, an estimated 500 kg of ice per MT of fish is used in the insulated trucks. The total estimated ice use for transportation is about 940 MT per day.

### 2.1.4. Processing in factory

As the supply chain is not well integrated, the processing plants maintain an iced storage facility for incoming raw material to make-up for the required quantity for the batch processing. At this stage ice demands also vary depending on the waiting time, based on our survey an average 500 kgs of ice usages is estimated per ton of fish in waiting area. Large quantity of chilled water at 5 °C to 8 °C is used during processing in 3 to 4 washing cycles and this is accessed about 10 times the surimi product (Park, 2005). Finally the surimi as a product is made in form of blocks of 10 kgs which undergo quick deep freezing in plate freezer for about 2 hours until their core temperature reaches -25 °C. To achieve this temperature from processing temperature of about 10 °C about 342.5 kJ per kg heat needs to be removed (Park, 2005).

#### 2.1.5. Cold storage

After deep freezing, the surimi blocks are packed in cardboard boxes and stored in cold storage for long time at temperature range of -18 to -30 ºC. We estimated 70 kW cooling load for a cold store having dimensions 28×28×7 $m^3$ to store 1500 MT of product (Saini et al., 2021a). For the estimation of total storage volume and cooling load we scaled up this value. The average storing time is estimated to be 5 months.

### 2.2. Shrimp cold chain

Shrimp supply chain has some similarity with surimi supply chain, however, the harvesting is mostly from ponds and hatcheries where shrimp is farmed. Thus, the time spent between post-harvest and pre-processing is smaller which helps quality assurance. India is the global leader in shrimp farming, the total production in the year 2020-21 was about 719847 MT out of which 82% was exported, that made an export earnings of 4.43 billion USD (MPEDA, 2021). The shrimp farms are located mostly in four states on the Eastern and the South-Eastern coast of India: West Bengal, Orissa, Andhra Pradesh, and Tamil Nadu. Field survey for data collection was carried out at a shrimp processing plant located at Kolkata (West Bengal) for this study. In the processing 45% of raw material yields as shrimp meat (Venugopal, 2021). Assuming 304 days per year production, average per day production is about 2370 MT for which 5260 MT/day of shrimp is harvested. For the estimation of cooling load, based on the field visits, we assumed that ice usage for 1 MT of raw material for shrimp in the harvesting, handling & pre-processing, and transportation and waiting stages are 1 MT, 0.2 MT and 1 MT, respectively. At the processing stage, the estimated chilled water requirement is about 4 times the raw material weight. Quick deep freezing is done for finished product at low temperature -35 °C. The average time of cold storage for shrimp is estimated as 1 month.

## 3. COOLING DEMANDS, REFRIGERATION AND REFRIGERANTS USAGE

The hourly averaged temperature bin data of Kolkata, Vishakhapatnam, & Chennai (the eastern and south eastern coast), and Mumbai, Veraval & Ratnagiri (the western coast), are plotted in Figure 2 (Mathur et al., 2017). It is observed from the Figure 2 that the variation in temperature bin data is not large.

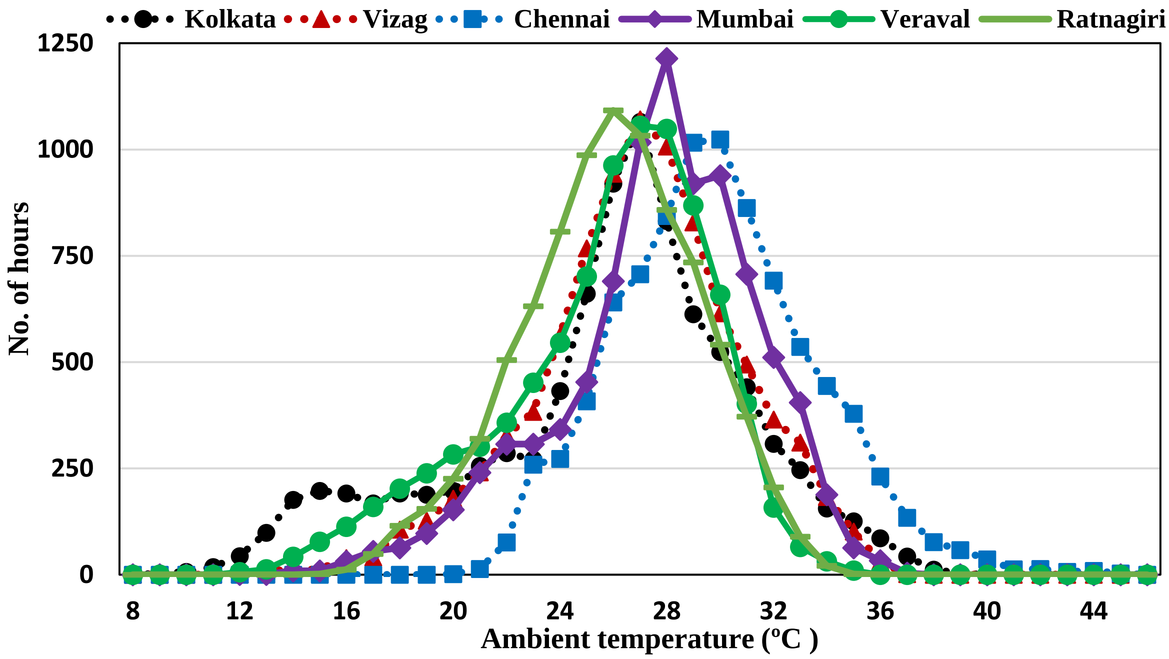


**Figure 2: Hourly ambient temperature bin data of major surimi and shrimp producing coastal sites**

Hence, for the estimation of annual energy consumption and total equivalent warming impact, climatic conditions of Mumbai on the western coast for surimi and that for Kolkata on the Eastern coast for shrimp were considered. While for cooling demand estimation, the ambient temperature is considered at a fixed 30 °C. As discussed, ice is predominantly used for preservation during harvesting, transport, pre-processing as well as at processing plants. There are many certified and uncertified ice producing plants by the marine products export development authority (MPEDA) near the coastal areas which supply the required ice. Estimated cooling demands to meet 470 MT per day surimi production and 2370 MT per day shrimp production including required ice, chilled water, deep freezing and cold storage in the downstream of the supply chains are tabulated in Table 1.

**Table 1: Cooling demands in surimi and shrimp cold chains as per 2021 production data**

| Parameter | Surimi | | | Shrimp | | |
|---|---|---|---|---|---|---|
| | Amount | Cooling load $\dot{Q}$ (kW) | Load % | Amount | Cooling load $\dot{Q}$ (kW) | Load % |
| Chilled water (7 ºC) | 4703 MT/day | 5250 | 12.0 | 9470 MT/day | 10550 | 11.6 |
| Ice (0 ºC) | 6020 MT/day | 33090 | 75.3 | 11580 MT/day | 63650 | 69.8 |
| Cold storage capacity (-20 ºC) | 70,500 MT | 2760 | 6.3 | 71100 MT | 2790 | 3.1 |
| Freezing (-35 ºC) | 470 MT/day | 2820 | 6.4 | 2370 MT/day | 14220 | 15.6 |

The alliance for an energy efficient economy (AEEE), carried out an assessment of the India's nationwide cooling demands for 2027, under a project by the Indo-German energy forum (Kumar et al., 2018). This study reported the cooling demands and refrigerants used in various sectors and future growths in these sectors in India. It also estimated the energy consumption and total $CO_2$ emissions. The study recorded some assessment of refrigerants used in India during 2017 and made a projection for 2027 with business as usual scenario. An intervention scenario was also discussed based on energy efficiency, changes in technologies and refrigerants, development of the cooling sector etc. for the year 2027. Further, the Ozone cell, Ministry of environment, forest & climate change (MoEF&CC) India along with the United Nations environment programme (UNEP) published a report on promotion of low GWP refrigerants for sustainable cooling technologies that have potential to be introduced at various stages of cold chains in India. This study suggested solutions such as low charge ammonia systems and cascade refrigeration systems based on some case studies (Ozone cell, 2021). In another study, the authors had discussed how cascade refrigeration system are more energy efficient for seafood processing and storage (Saini et al., 2021a). In the current study, the energy consumption and emissions for three scenarios, *Scenario 0*: refrigerant mix as estimated by Kumar et al., (2018), *Scenario 1*: refrigerant mix as predicted for 2027 with interventions and *Scenario 2*: use of fully natural refrigerants mix are discussed. All the three scenarios are summarized in Table 2.

Single-stage vapor compression refrigeration systems were considered for chilled water and ice production for all the three scenarios. While, for cold storage and freezing applications, double-stage vapor compression refrigeration systems with intercooling were considered for *Scenario 0 and Scenario 1*. For $CO_2$ in *scenario 1*, a transcritical parallel compression booster refrigeration system was considered. For *Scenario 2* cascade refrigeration system having $NH_3$ in high temperature circuit and either $CO_2$, R1270 or R170 in low temperature circuit was considered for cold storage and freezing application (Saini et al., 2021a).

**Table 2: Refrigeration type and refrigerant use in various applications**

| Scenarios | Refrigerant mix<br>Chilled water & Ice | Cold storage | Deep freezing |
|---|---|---|---|
| *Scenario 0* | Single-stage: R134a: 20%, R22: 10% R404A: 5%, $NH_3$: 65% | Double-stage: R134a: 5%, R22: 10%, R404A: 10%, $NH_3$: 75% | Double-stage: R134a: 65%, R404A: 20%, R407/R410A: 10%, $NH_3$: 5% |
| *Scenario 1* | Single-stage: R134a: 10%, R404A: 5%, $NH_3$:85% | Double-stage: R134a: 5%, R404A: 5%, $NH_3$: 90% | Double-stage: R134a: 50%, R404A: 5%, R407/R410A: 30%, $CO_2$: 15% |
| *Scenario 2* | Single-stage: $NH_3$: 85%, R290/R1270:15% | Cascade system: $NH_3$-$CO_2$: 60%, $NH_3$-R1270: 20%, $NH_3$-R170: 20% | Cascade system: $NH_3$-$CO_2$: 60%, $NH_3$-R1270: 20%, $NH_3$-R170: 20% |

## 4. MATHEMATICAL MODEL

Mathematical models were developed for all the configurations assuming steady flow steady-state condition across each component, while pressure drops in pipes and all heat exchangers were neglected. Isenthalpic expansion was assumed in all expansion valves. The thermodynamic state points for each operating condition were obtained iteratively utilizing the EES platform (Klein, 2018). In thermodynamic model of both the systems, basic mass and energy balance equations were applied at each component. Coefficient of performance (COP) of the refrigeration systems were calculated using Eq. 1. In this equation, $\dot{Q}$ (kW) is cooling load in a particular evaporator as mentioned in Table 1 and $\dot{W}_{comp}$ (kW) is compressor power consumption in respective compressor. Compressor power consumption is calculated using Eq. 2, in which $\dot{m}_{ref}$ in kg.s$^{-1}$, is refrigerant mass flow rate and $h_{in}$ & $h_{out}$ in kJ.kg$^{-1}$, are enthalpy of refrigerant at inlet and outlet. Refrigerant mass flow rate $\dot{m}_{ref}$ is calculated using Eq. 3. Compressor isentropic efficiency ($\eta_s$) for all the compressors are given by Eq. 4, where R is the compression ratio of refrigerant (Saini et al., 2021b).

$$COP_{VCRS} = \frac{\dot{Q}_{cooling}}{\dot{W}_{comp}} \qquad \text{Eq. (1)}$$

$$\dot{W}_{comp} = \frac{\dot{m}_{ref}(h_{out,s} - h_{in})_{compressor}}{\eta_s} \qquad \text{Eq. (2)}$$

$$\dot{m}_{ref} = \frac{\dot{Q}_{cooling}}{(h_{out,s} - h_{in})_{evaporator}} \qquad \text{Eq. (3)}$$

$$\eta_s = 0.874 - 0.0135 * R \qquad \text{Eq. (4)}$$

Annual energy consumption (kWh) is calculated using Eq. 5 assuming year-round operation, where $H$ is the number of hours for particular ambient temperature $T$.

$$AEC = \sum_{i=T_{min}}^{T_{max}} \frac{\dot{Q}_{ch} + \dot{Q}_{ice} + \dot{Q}_{cs} + \dot{Q}_{pf}}{COP_T} * H_T \qquad \text{Eq. (5)}$$

Total equivalent warming impact ($TEWI$) is a significant parameter to assess $CO_2$ emissions from a refrigeration system. The TEWI is calculated using Eq. 6. Total refrigerant leakage ($M_{leakage}$) in kg, is computed from total refrigerant charge and refrigerant leakage rate. In this study, refrigerant charge is considered as 3 kg of refrigerant per kW of refrigeration load and annual refrigerant leakage is taken as 15% (Saini et al., 2021b). Recycling factor ($\alpha$) is taken 95% while GWP values for $NH_3$, R134a, R404A, R22, R410A, R407C, $CO_2$, R290, R1270 and R170 are considered as 0, 1430, 3943, 1810, 2088, 1774, 1, 1810 & 3943 respectively. The electricity regional conversion factor ($\beta$) is taken as 0.9 (kg $CO_2$ per kWh), which depend upon the regional energy mix (Lata & Gupta, 2021).

$$TEWI = \left(M_{leakage} * n + M_{charge}(1 - \alpha)\right) GWP + \beta * AEC * n \qquad \text{Eq. (6)}$$

Net value of AEC and TEWI are estimated using the weighted average method in which percentage of refrigerant for particular application and their respective AEC and TEWI value were considered.

## 5. RESULTS AND DISCUSSION

### 5.1. Coefficient of performance (COP)

Performance of all the systems with the mentioned refrigerants for particular application were estimated through simulation for the ambient conditions of Mumbai and Kolkata. Coefficient of performance (COP) at an ambient temperature of 30 ºC for all the refrigerants along with the analyzed refrigeration systems with various refrigerants are given in Table 3. In the analysis we considered evaporator temperatures 5 ºC lower than the mentioned product/application temperature in Table 2 and condenser temperature 5 ºC higher than ambient. Among all the analyzed refrigerants $NH_3$ has the highest COP for all the applications. Although COP of cascade system in freezing application is higher compare to $NH_3$ from all investigated refrigerants.

**Table 3: COP of refrigeration systems with different refrigerants at 30 °C**

| Application/ Refrigerant mix | Single-stage system | | Two-stage system | | Cascade system | |
|---|---|---|---|---|---|---|
| | Chilled water | Ice | Cold storage | Deep freezing | Cold storage | Deep freezing |
| $NH_3$ | 5.86 | 4.08 | 2.31 | 1.51 | - | - |
| R134a | 5.04 | 3.87 | 1.96 | 1.22 | - | - |
| R404A | 4.56 | 3.48 | 1.65 | 0.99 | - | - |
| R22 | 5.08 | 3.95 | 2.08 | 1.34 | - | - |
| R410A | 4.69 | 3.62 | 1.84 | 1.16 | - | - |
| R407C | 5.33 | 4.11 | 2.09 | 1.34 | - | - |
| R290 | 5.56 | 4.24 | - | - | - | - |
| R1270 | 5.54 | 4.24 | - | - | - | - |
| $CO_2$ | - | - | - | 0.95 | - | - |
| $NH_3$-$CO_2$ | - | - | - | - | 2.25 | 1.89 |
| $NH_3$-R1270 | - | - | - | - | 2.46 | 2.04 |
| $NH_3$-R170 | - | - | - | - | 2.22 | 1.87 |

### 5.2. AEC and TEWI in *Scenario 0*

AEC and TEWI values per MT of products for all the four applications of surimi and shrimp cold chain for *Scenario 0* are presented in Figure 3 and Figure 4. AEC per MT of product for surimi and shrimp cold chains are 569 kWh and 267 kWh. In surimi cold chain AEC for ice production is the highest with a share of 63.4% and that of chilled water is the lowest 7.6%. Similarly, for shrimp cold chain AEC for ice production is the highest with a share of 50.2%, and cold storage has the lowest 4.2%. The TEWI per MT of product for surimi and shrimp cold chains are 9255 kgs of $CO_2$ equivalent and 4352 kgs of $CO_2$ equivalent, respectively. Percentage share of TEWI in both cold chains are almost similar to the AEC share. In *Scenario 0,* the net AEC for surimi and shrimp cold chains are estimated as 81.27 GWh and 192.25 GWh, respectively based on simulation. Similarly, the estimated net TEWI for surimi and shrimp cold chains are $1322\times10^6$ kgs of $CO_2$ equivalent and $3135\times10^6$ kgs of $CO_2$ equivalent, respectively.

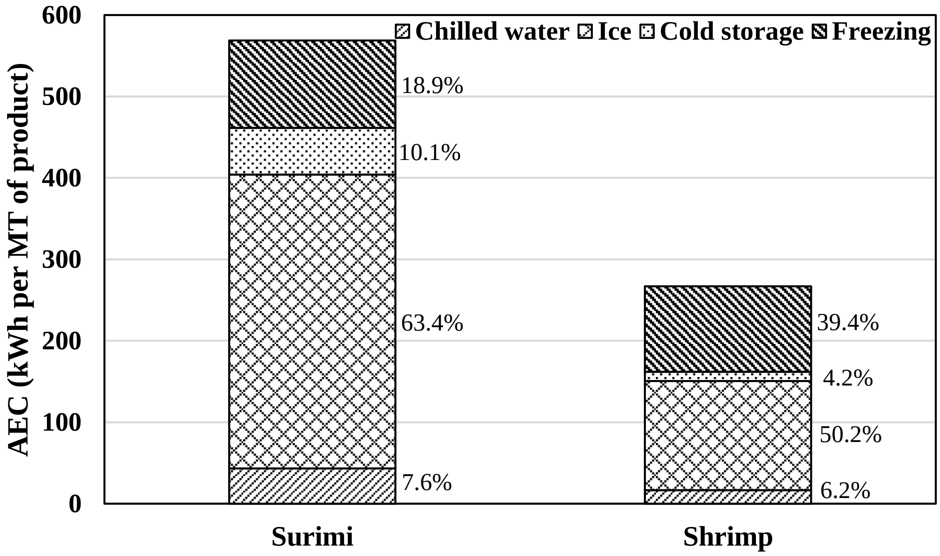


**Figure 3: Energy footprint of supply side of cold chain for surimi and shrimp in *Scenario 0***

Due to higher cooling requirement in cold chain at all the stages, surimi has about double AEC and TEWI value per MT of product. Ice production consumes the highest AEC and contribute the highest emissions. To reduce the energy consumption and emissions, cold chain stages where ice requirement are high need interventions. In surimi the harvesting stage consumes the maximum ice, on-board refrigerated sea water (RSW) system can be deployed which can reduce ice requirements and improved quality of catch (Saini et al. 2019).

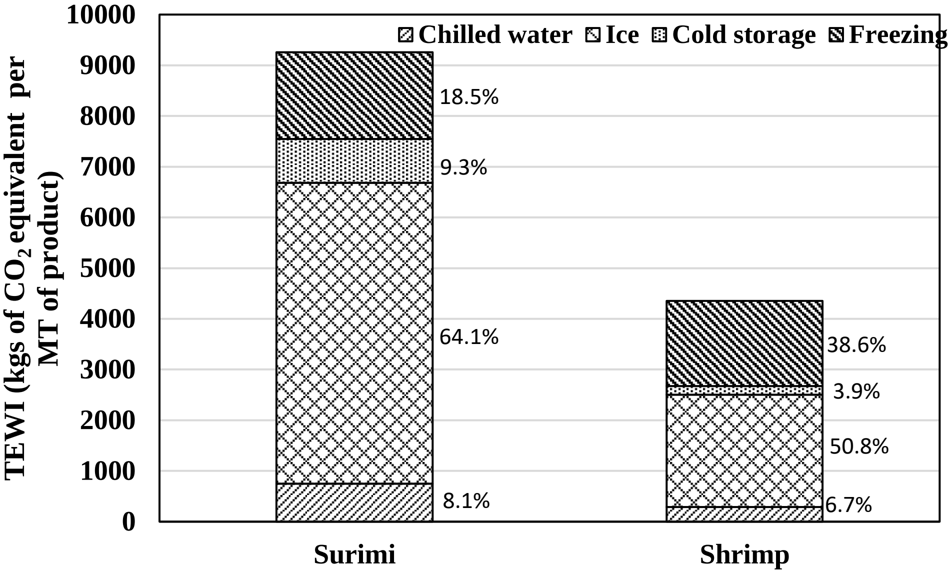


**Figure 4: Environmental footprint of supply side of cold chain for surimi and shrimp in *Scenario 0***

## 5.3. Comparison of AEC & TEWI for all scenarios

The estimated AEC and TEWI of the surimi and shrimp cold chains per MT of product for all the three considered scenarios of refrigerant mix are presented in Figure 5 and Figure 6. As shown in Figure 5, change in AEC between the *Scenario 0* and *Scenario 1* are negligible but AEC for *Scenario 2* is about 6.6% and 3.5% less compared to *Scenario 0* for surimi and shrimp respectively. This reduction in AEC values are a result of high performance of the cascade system at the lower cooling temperature of cold storage and freezing applications.

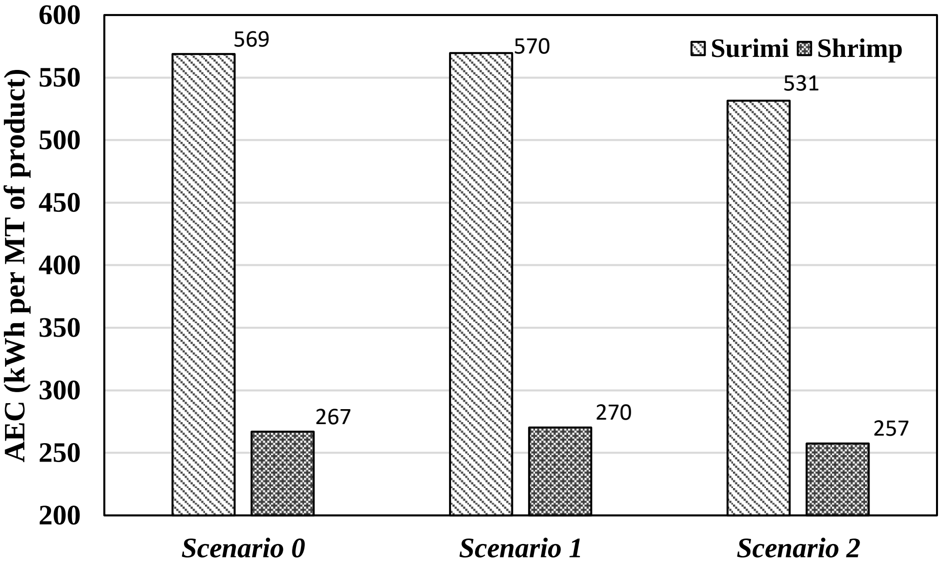


**Figure 5: AEC per MT of product for all three analysed cases**

As shown in Figure 6, TEWI value of surimi cold chain in the *Scenario 1* and *Scenario 2* are about 7.5% and 22.5% less compare to the *Scenario 0*. Similarly, TEWI value of shrimp cold chain in the *Scenario 1* and *Scenario 2* are about 5.7% and 20.1% less compare to the *Scenario 0*. This change in the TEWI values are a result of combined effect of change in GWP value of refrigerant mix and the AEC value in a particular cold chain.

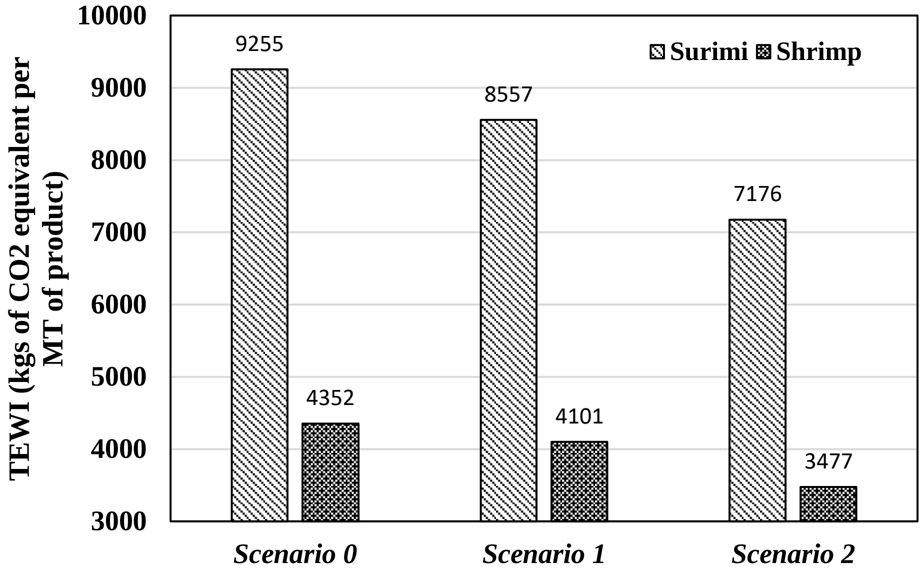


**Figure 6: TEWI per MT of product for all three analyzed cases**

## 6. BARRIERS IN ADOPTION OF LOW GWP REFRIGERANTS: INDIAN CONTEXT

As emphasized in introduction section India has put forward concrete steps to combat the rising climatic changes by phasing down the HFC refrigerants. However, it is contextual to mention here that there are many barriers to the intended transition of the Indian refrigeration industry. Based on a survey conducted in India, Bhattacharyya (2010) highlighted various constraints in adoption of low GWP natural refrigerants such as *legislation for standards and policies*, *lack of funding and financial support*, *non-availability of technology and safety measures*, *insufficient training for technicians*, and *absence of markets and marketing of appliances using natural refrigerants*. Sanguri et al. (2021) also reported a study to determine the major barriers in adoption of low GWP refrigerants in India. They highlighted 20 major barriers and categorized them into nine levels and concluded that *lack of government incentives* is the most significant barrier faced by the industry followed by *lack of R&D facilities for the development of low GWP refrigerants*. G*overnment's inefficiency to enforce regulations uniformly*, and *ambiguity in regulations defined by the government* are other prominent barriers. With no formal legislation mandating the use of natural refrigerants for refrigeration applications in the industrial, commercial and domestic sectors, the uptake of natural refrigerants becomes voluntary, and hence has not been very significant. The eventual transitions of the refrigeration market towards low GWP refrigerants have many other challenges related to cost, safety, and availability. Moreover, the levels of knowledge and confidence about performance of various alternative refrigerants in Indian context is lacking, which is also a formidable barrier in their adoption.

## 7. CONCLUSIONS

In this study, we estimated the cooling demands in cold chains for surimi and shrimp production in India. For the assessment of corresponding energy consumption and environmental impact, we analyzed total three scenarios, two of which are based on refrigerant mix discussed in a report and a third scenario of shifting to fully natural refrigerants. Performance of these refrigerants were computed by simulating: single-stage vapor compression refrigeration system for chilled water and ice production applications, two-stage vapor compression refrigeration system for cold storage and deep freezing applications, and cascade system for cold storage and deep freezing application using natural refrigerants. AEC and TEWI are determined assuming ambient conditions of Mumbai and Kolkata as representative sites for surimi and shrimp production, respectively. The advantage of using natural refrigerants in terms of AEC is found to be a reduction of 6.5% for surimi and 3.5% for shrimp cold chain. While reduction in TEWI was found to be 22.5% for surimi and 20.1% for shrimp cold chain. However adoption of these natural refrigerants by the Indian refrigeration industry may not be smooth as there are various prominent barriers, some of which are also discussed here.

## ACKNOWLEDGEMENTS

This work was supported under grant BT/IN/INNO-Indigo/12/NK/2017-18 from DBT India, and NFR Norway project number 281262 (ReValue: Innovative technologies for improving resource utilization in the Indo-European fish value chains).

## NOMENCLATURE

| | |
|---|---|
| $\dot{Q}_{cooling}$ | Cooling load in evaporators (kW) |
| $\dot{W}_{comp}$ | Power consumption in compressor (kW) |
| $\dot{m}_{ref}$ | Mass flow rate (kg s$^{-1}$) |
| $m_{charge}$ | Refrigerant charge (kg) |
| AEC | Annual energy consumption (kWh) |
| COP | Coefficient of performance |
| CRS | Cascade refrigeration system |
| GWP | Global warming potential |
| *h* | Specific enthalpy (kJ kg$^{-1}$) |
| H | Number of hours |
| MT | Metric tonnes |
| n | Number of operational years |
| *R* | Ratio of discharge to inlet pressure |
| T | Temperature (ºC) |
| TEWI | Total equivalent warming impact |

Greek symbols:

| | |
|---|---|
| $\eta$ | Efficiency (%) |
| $\alpha$ | Recycling factor |
| $\beta$ | Electricity regional conversion factor |

Subscripts:

| | |
|---|---|
| *ch* | Chilled water refrigerant line |
| *cs* | Cold storage refrigerant line |
| *ice* | Ice refrigerant line |
| in | Inlet |
| out | Outlet |
| *pf* | Plate freezer refrigerant line |
| s | Isentropic |

## REFERENCES

Bhattacharyya, s., 2010. Natural refrigerants- the Indian perspective. Accessed from: http://www.ammonia21.com/files/pdf_699.pdf, Accessed on: 30 December 2021.

Chatterjee, P. K., 2022. Expectations in the post-COP26 era. Cooling India. Available on: https://www.coolingindia.in/expectations-in-the-post-cop26-era/ Accessed on: 13 January 2022.

Dasgupta, M.S., Routroy, S., Widell, K.N., Bhattacharyya, S., Thakur, M., 2019. A Strategy for improved temperature control in the supply and processing stages of Surimi cold chain in India. IIR Int. Congress Refriger. DOI. https://doi.org/10.18462/iir.icr.2019.131.

FAO, 2020. The state of world fisheries and aquaculture 2020, sustainability in action, Rome. ISBN 978-92-5-132692-3. https://doi.org/10.4060/ca9229en

Klein, S. A., 2018. EES – Engineering Equation Solver, Version 10.522, 2018-10-30 F-Chart Software.

Kumar, S., Sachar, S., Kachhawa, S., Goenka, A., Kasamsetty, S., George, G. (2018). Demand Analysis of Cooling by Sector in India in 2027. New Delhi: Alliance for an Energy Efficient Economy. Accessed from: https://aeee.in/projects/demand-analysis-for-cooling-by-sector-in-india-in-2027/ Accessed on: 18 January 2022.

Lata, M., & Gupta, D. K., 2020. Performance evaluation and comparative analysis of trans-critical $CO_2$ booster refrigeration systems with modified evaporative cooled gas cooler for supermarket application in Indian context. International Journal of Refrigeration, 120, pp. 248-259.

Mathur, J., Garg, V., Murthy, V., 2017. Indian weather data. ISHRAE.

MPEDA, 2 June 2021. India exports 11,49,510 MT of seafood during 2020-21. MPEDA press release. Accessed from: https://mpeda.gov.in/?page_id=5581 Accessed on: 10 January 2022.

NAAS 2019. Saving the Harvest: Reducing the Food Loss and Waste; Policy Brief No. 5; National Academy of Agricultural Sciences: New Delhi, India, 2019; 10p.

NCCD. 2015. All India cold-chain infrastructure capacity (Assessment of status & gap), Delhi. *(www.nccd.gov.in )*

Ozone cell, 2021. Study on cold-chain sector in India for promoting non-ODS and low GWP refrigerants. Ozone cell, Ministry of Environment, Forest & Climate Change, Government of India. Accessed from: http://ozonecell.nic.in/home-page/resource-informations/reports-publications/study-on-cold-chain-sector-in-india-for-promoting-non-ods-and-low-gwp-refrigerants/ Accessed on: 14 January 2022.

Park, J. W. (2005). *Surimi and surimi seafood*. CRC press.

Raghuram, G., & Asopa, V. N. (2008). Issues in Infrastructure for Export of Marine products from India.

Rais, M.; Acharya, S.; Sharma, N. Food processing industry in India: S&T capability, skills and employment opportunities. J. Rural. Dev. **2014**, 32, 451–478.

Saini, S. K., Dasgupta, M. S., Widell, K. N., & Bhattacharyya, S. (2021a). Comparative analysis of a few novel multi-evaporator CO2-NH3 cascade refrigeration system for seafood processing & storage. *International Journal of Refrigeration*, *131*, 817-825. https://doi.org/10.1016/j.ijrefrig.2021.07.017

Saini, S. K., Dasgupta, M. S., Widell, K. N., & Bhattacharyya, S. (2021b). Natural refrigerant based cascade system for seafood application. In proceeding of the 48th National Conference on Fluid Mechanics and Fluid Power (FMFP), Pilani, India.

Saini, S. K., Dasgupta, M. S., Widell, K. N., & Bhattacharyya, S. (2019). Thermal and economic analysis of an on-board compensatory refrigeration system for small fishing boats. In Proceedings of the 25th National and 3rd International ISHMT-ASTFE Heat and Mass Transfer Conference, Roorkee, India.

Sanguri, K., Ganguly, K., & Pandey, A. (2021). Modelling the barriers to low global warming potential refrigerants adoption in developing countries: A case of Indian refrigeration industry. *Journal of Cleaner Production*, *280*, 124357. https://doi.org/10.1016/j.jclepro.2020.124357

Sharma, H., Swain, M., & Kalamkar, S. S. (2018). Supply chain and market infrastructures for Marine Fishery in Gujarat. *International Journal of Fisheries and Aquatic Studies*, 6(4): 192-198.

Sultan, F. A., Routroy, S., & Thakur, M. (2021). A simulation-based performance investigation of downstream operations in the Indian Surimi Supply Chain using environmental value stream mapping. *Journal of Cleaner Production*, *286*, 125389. https://doi.org/10.1016/j.jclepro.2020.125389

Venugopal, V. (2021). Valorization of seafood processing discards: Bioconversion and bio-refinery approaches. *Frontiers in Sustainable Food*, *5*. https://doi.org/10.3389/fsufs.2021.611835

# Response to Reviewers

## Reviewer 1

*Good paper, fluent English, interesting topic. Some remarks:*

Comment 1: *Nomenclature is incomplete, most symbols are missing, some are not even described in the text (e.g. R in Eq.4).*

Response 1: Authors regret the ambiguity. The manuscript has been revised and corrected all the discrepancies related to the nomenclature. In the revised manuscript, we incorporated all the symbols and abbrevations used.

Comment 2: *Are you sure that 95% of the used refrigerant (apart from leakage) is recycled? Aren't there problems with contamination among fluids, contamination with other chemicals or from mototr burns, etc which prevent from a correct recycle.*

Response 2: Authors agree that a part of the refrigerant get contaminatd and burnt out during the process. However, The Intergovenmental Panel of Climate Change (IPCC) recommends that by following good recycling practices, 70% to 95% of the refrigerants can be recovered/recycled depending on the equipment class. In practice the refrigerant recovery rate from a system with a refrigerant charge greater than 100 kg would be expected to be 90% to 95% of the remaining charge after leakage, and around 70% for equipement with smaller chagres. Thus, considering the industrial refrigeration with large amount of charge, in the analysis we considered 95% recovery/recycling of the refrigerant after leakage. We also provided a refrence for the same in the manuscript.

Comment 3: *The CO2- only system for freezing: what configuration are you considering?*

Response 3: For the analysis, we considered a transcritical parallel compression booster refrigeration system and also mentioned it in the revised manuscript.

Comment 4: *Table 3, what evaporating temperatures?*

Response 4: Thanks for the observation. In the analysis we considered evaporator temperatures 5 ºC lower than the mentioned product/application temperature in Table 2 and condenser temperature 5 ºC higher than ambient. We also mentioned this in the revised manuscript.

## Reviewer 2

*Agreement with 1st reviewer.*