Natural Refrigerant based Cascade Refrigeration System for Seafood Application

International Webinar on Practicality and Applicability of Natural Working Fluids

BITS Pilani
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SINTEF

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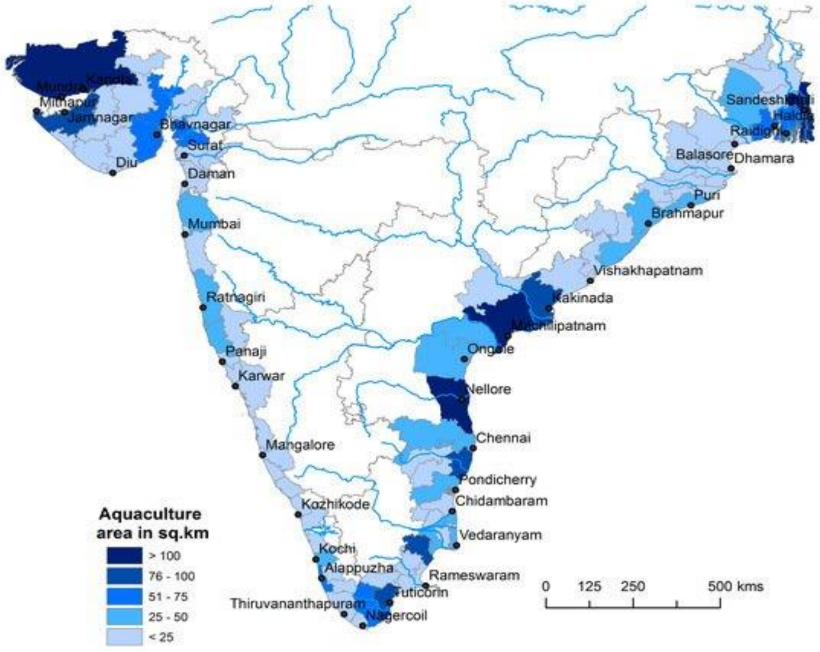
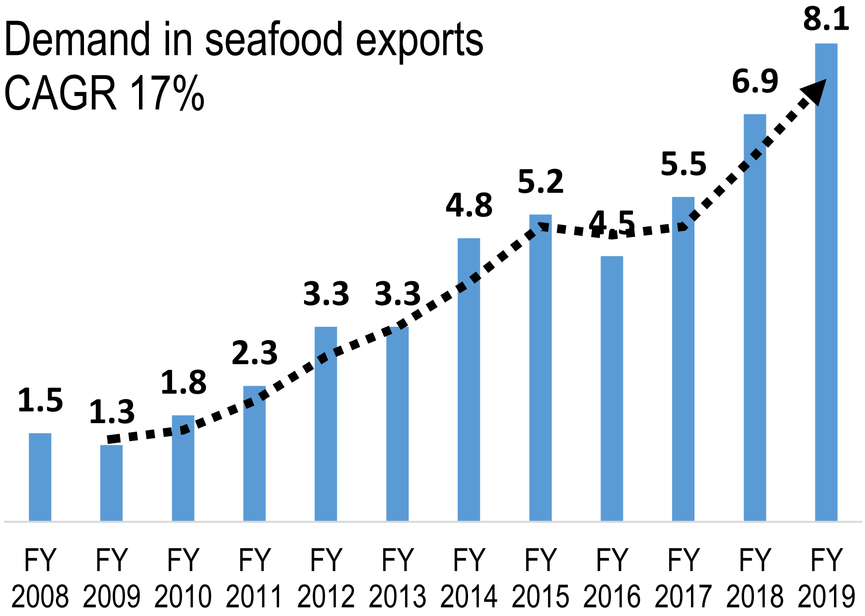
Seafood Status of India

- Coastline 8000 km^2 along with inland water resources, an estimated production 12.6 Mt (2019-20)
- 6.3% of global production (NFDB, 2020), 2nd largest seafood producers (marine +Aquaculture)
- 10.23% exported, 4th biggest exporter
- Seafood export earnings was $6.68 billion, about 1.2% of GDP, major contributor frozen seafood
- Per capita consumption: 6.5 kg → 9 kg in 2030





Source: Prasad et al., (2019). Assessment of coastal aquaculture for India from Sentinel-1 SAR time series. *Remote Sensing*, *11*(3), 357., Directorate General of Foreign Trade, CRISIL Research

Refrigeration in Seafood Preservation

- Highly perishable, 1/3rd of produce lost or wasted globally (FAO 2019)
- Impacts food security, food quality & safety, economical development and environment
- Low temperature, ensures longer shelf life retarding microbiological, physical and chemical changes
- Chilling (~0°C), superchilling(-3°C), freezing (-30°C to -50°C) and cold storage (-18°C to -30°C)
- About 20 kWh energy/ton-fish is consumed in processing | 50-70% in freezing and cold storage

Landing site

Movement of chilled fish

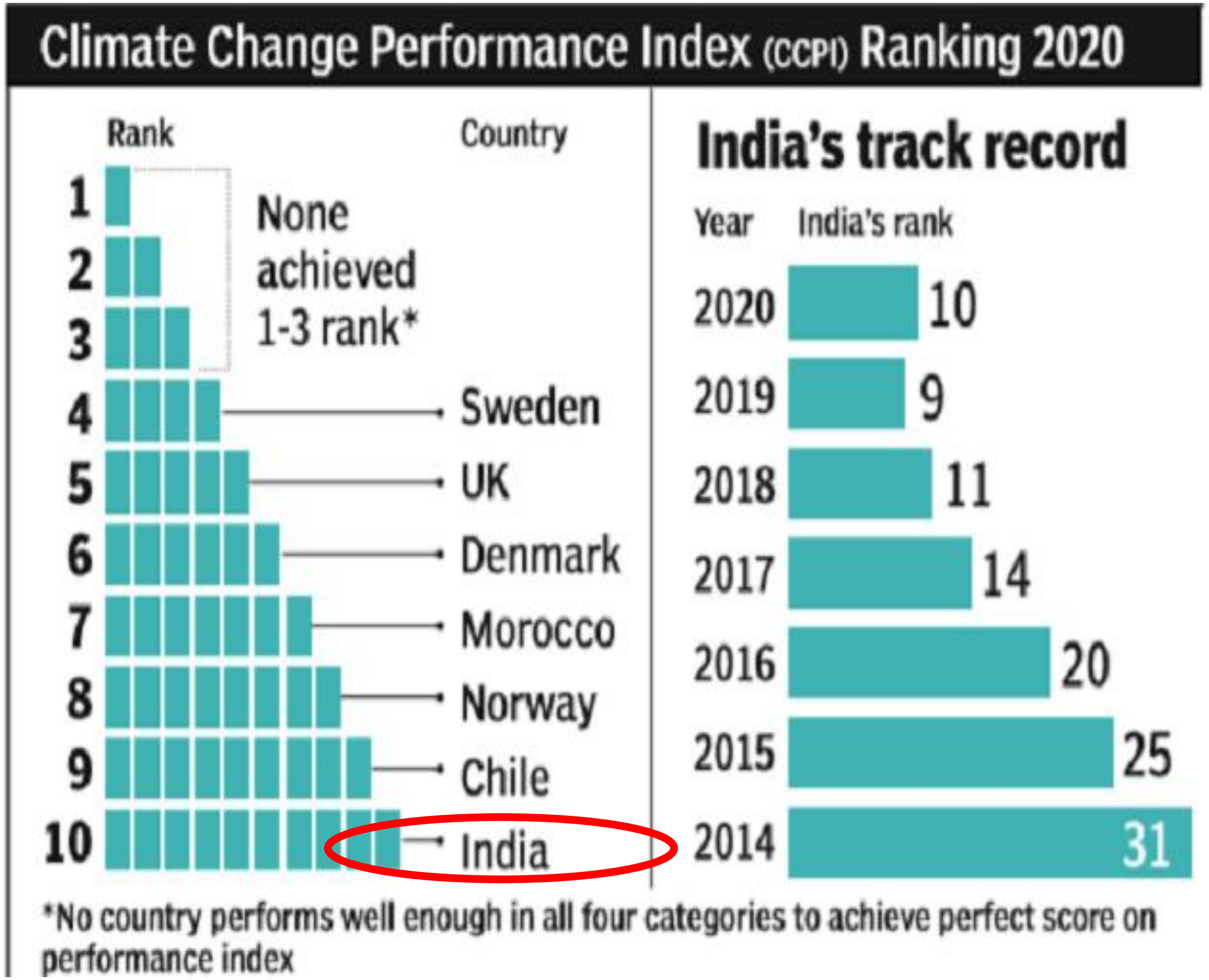
Pre-processing

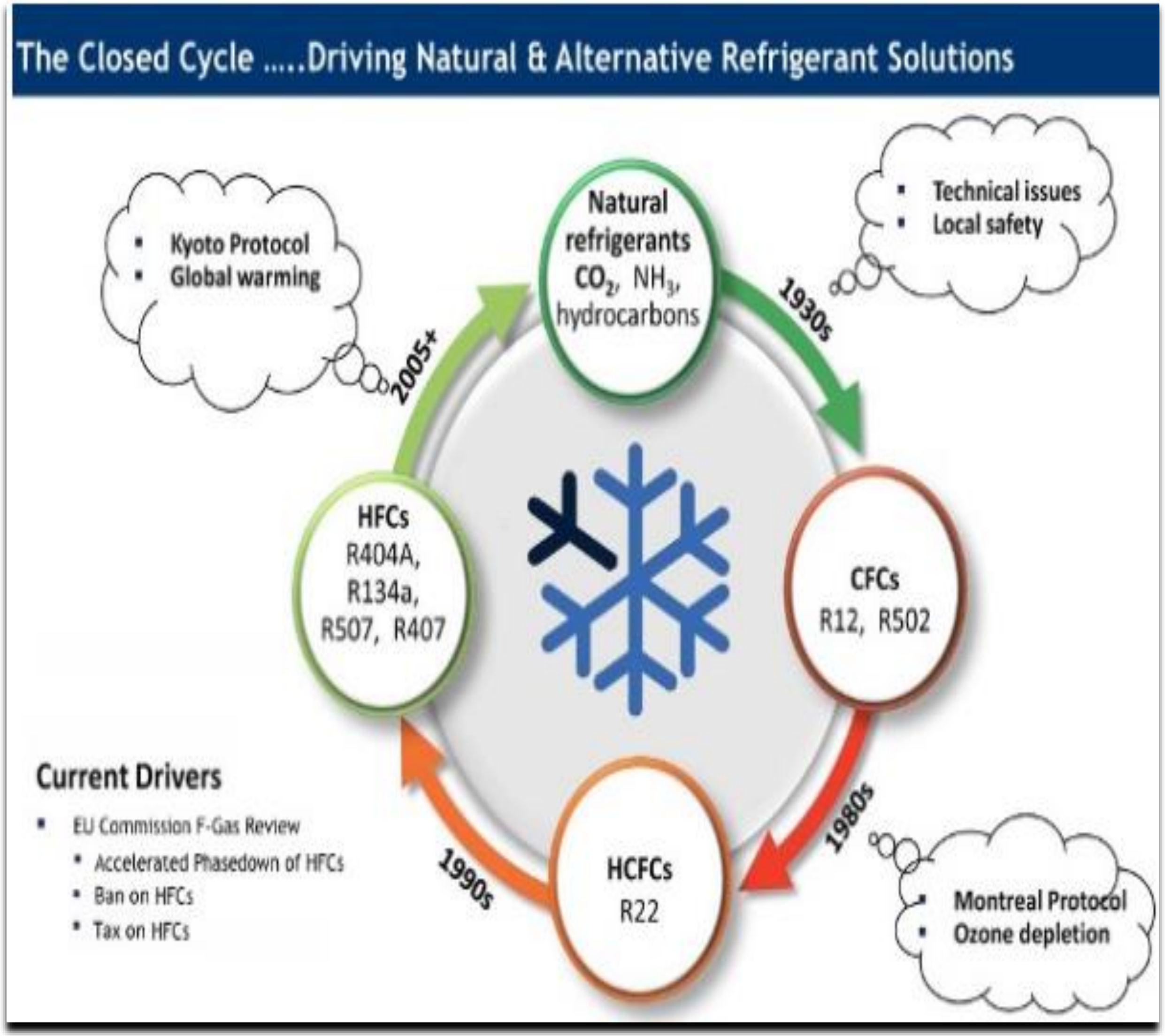
Freezing

Cold storage

Why Natural Refrigerants?

Major refrigerants in use | R22, R23, R404A, R410A, R507C & NH_3, most have high GWP





a. GHG emission 40% b. Renewable energy 20%

c. Energy efficiency 20% d. Climate policy 20%

Low GWP Refrigerant Choices

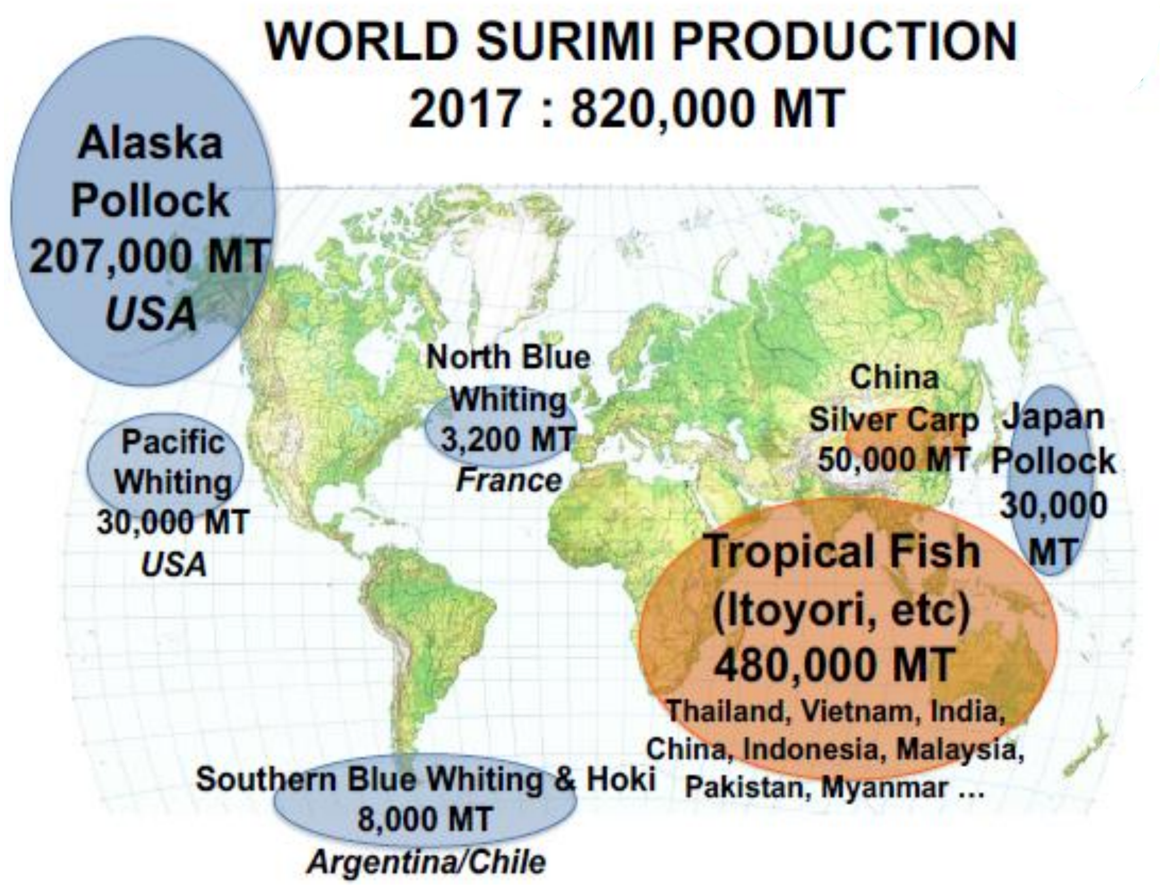
IUPAC name	Structure	ASHRAE designation	GWP_{100}
Hydrocarbons and dimethylether			
Ethane	$CH_3\text{-}CH_3$	R-170	6[†]
Propene (propylene)	$CH_2\text{=}CH\text{-}CH_3$	R-1270	2[†]
Propane	$CH_3\text{-}CH_2\text{-}CH_3$	R-290	3[†]
Methoxymethane (dimethylether)	$CH_3\text{-}O\text{-}CH_3$	R-E170	1[†]
Cyclopropane	$\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}$	R-C270	86
Fluorinated alkanes (HFCs)			
Fluoromethane	CH_3F	R-41	116[†]
Difluoromethane	CH_2F_2	R-32	677[†]
Fluoroethane	$CH_2F\text{-}CH_3$	R-161	4[†]
1,1-Difluoroethane	$CHF_2\text{-}CH_3$	R-152a	138[†]
1,1,2,2-Tetrafluoroethane	$CHF_2\text{-}CHF_2$	R-134	1120[†]
Fluorinated alkenes (HFOs) and alkynes			
Fluoroethene	$CHF\text{=}CH_2$	R-1141	<1[†]
1,1,2-Trifluoroethene	$CF_2\text{=}CHF$	R-1123	3
3,3,3-Trifluoroprop-1-yne	$CF_3\text{-}C{\equiv}CH$	NA	1.4
2,3,3,3-Tetrafluoroprop-1-ene	$CH_2\text{=}CF\text{-}CF_3$	R-1234yf	<1[†]
(E)-1,2-difluoroethene	$CHF\text{=}CHF$	R-1132(E)	1
3,3,3-Trifluoroprop-1-ene	$CH_2\text{=}CH\text{-}CF_3$	R-1243zf	<1[†]
1,2-Difluoroprop-1-ene[§]	$CHF\text{=}CF\text{-}CH_3$	R-1252ye[§]	2
(E)-1,3,3,3-tetrafluoroprop-1-ene	$CHF\text{=}CH\text{-}CF_3$	R-1234ze(E)	<1[†]
(Z)-1,2,3,3,3-pentafluoro-prop-1-ene	$CHF\text{=}CF\text{-}CF_3$	R-1225ye(Z)	<1[†]
1-Fluoroprop-1-ene[§]	$CHF\text{=}CH\text{-}CH_3$	R-1261ze[§]	1
Fluorinated oxygenates			
Trifluoro(methoxy)methane	$CF_3\text{-}O\text{-}CH_3$	R-E143a	523[†]
2,2,4,5-Tetrafluoro-1,3-dioxole	$\text{-}O\text{-}CF_2\text{-}O\text{-}CF\text{=}CF\text{-}$	NA	1
Fluorinated nitrogen and sulfur compounds			
N,N,1,1-tetrafluormethaneamine	$CHF_2\text{-}NF_2$	NA	20
Difluoromethanethiol	$CHF_2\text{-}SH$	NA	1
Trifluoromethanethiol	$CF_3\text{-}SH$	NA	1
Inorganic compounds			
Carbon dioxide	CO_2	R-744	1.00[†]
Ammonia	NH_3	R-717	<1[†]
Current HFCs and HCFCs			
Pentafluoroethane	$CF_3\text{-}CHF_2$	R-125	3170[†]
R-32/125 (50.0/50.0)	Blend	R-410A	1924[†]
Chlorodifluoromethane	$CHClF_2$	R-22	1760[†]
1,1,1,2-Tetrafluoroethane	$CF_3\text{-}CH_2F$	R-134a	1300[†]

- Comprehensive screening on PubChem database
- A few pure fluids possess the combination of chemical, environmental, thermodynamic, & safety properties necessary for a refrigerant and that these fluids are at least slightly flammable

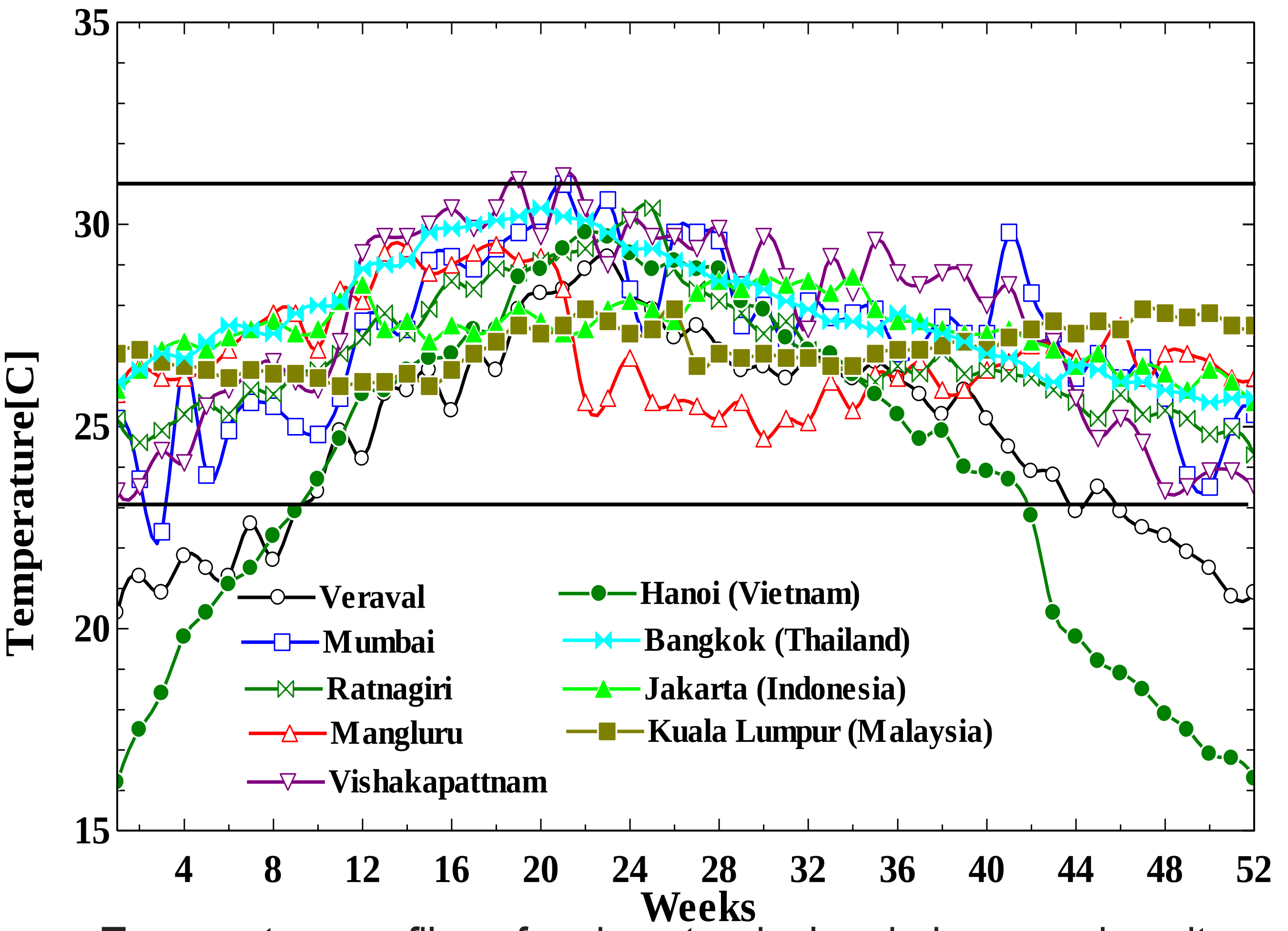
McLinden, M. O., Brown, J. S., Brignoli, R., Kazakov, A. F., & Domanski, P. A. (2017). Limited options for low-global-warming-potential refrigerants. Nature Communications, 8(1), 1-9

Surimi (Seafood) Producing Sites

India's annual production of surimi is about 90,200 tonnes, ~11% of total global production



Global surimi production sites



Temperature profiles of various tropical surimi processing sites

Cooling Demands & Operating Conditions

Production capacity: 10 tpd (Kaiko Surimi, Mumbai)

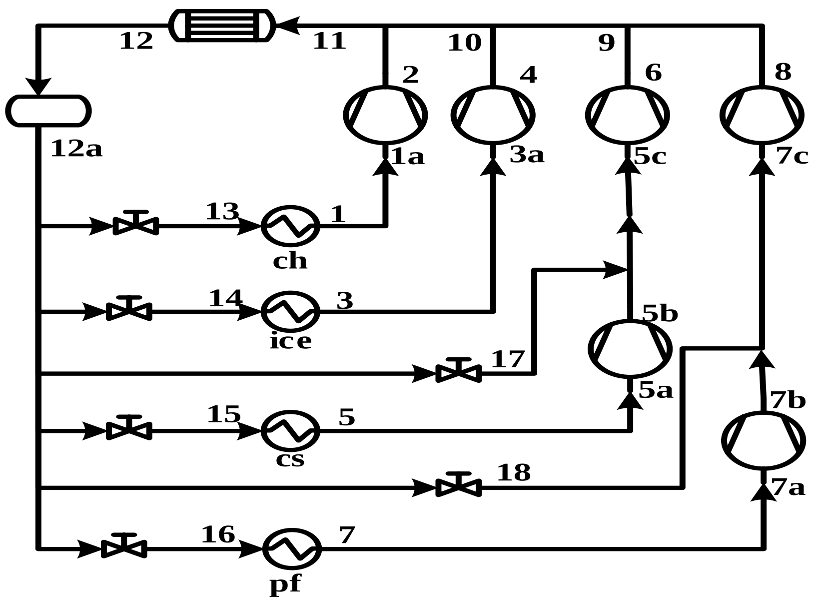
Cooling demands estimated for various temperature applications

Parameter	Evap	Amount	Product Temp (°C)	Evaporation Temp (°C)	Cooling load (kW)	Load %
Chilled water	ch	100 t/d	7	2	115	38.4
Ice	ice	10 t/d	0	-5	55	18.3
Cold storage	cs	1500 t	-20	-25	70	23.3
Freezing	pf	10 t/d	-35	-40	60	20.0

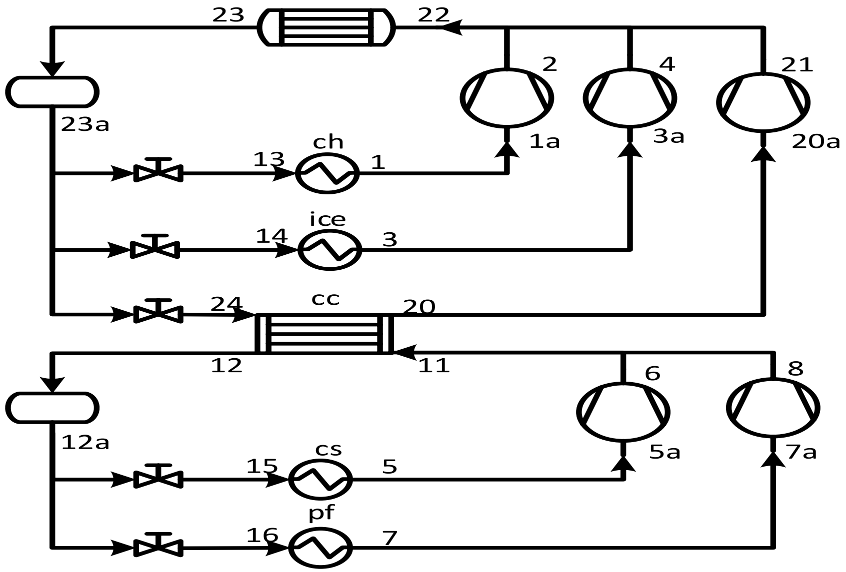
Operating condition used in the simulation

Parameters	Values (°C)
Suction superheat in ch and ice line	5
Suction superheat in cc and cs line	10
Suction superheat in pf line	20
Subcooling	0
Approach temperature	5
Cond temp.	15-45

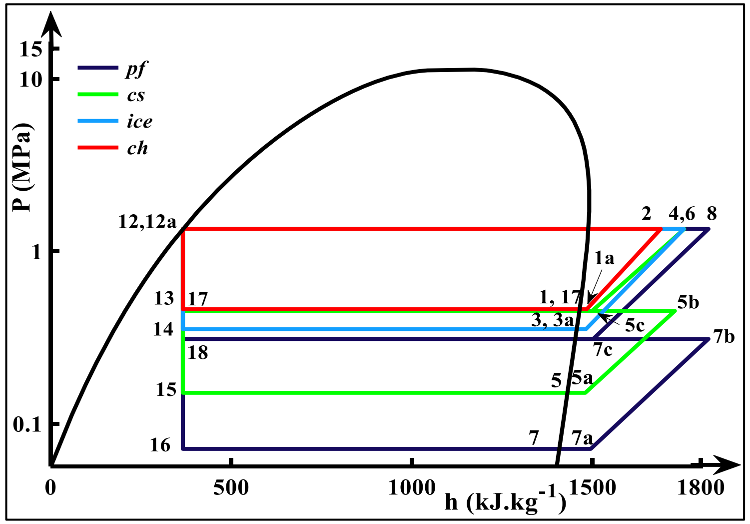
Refrigeration Systems



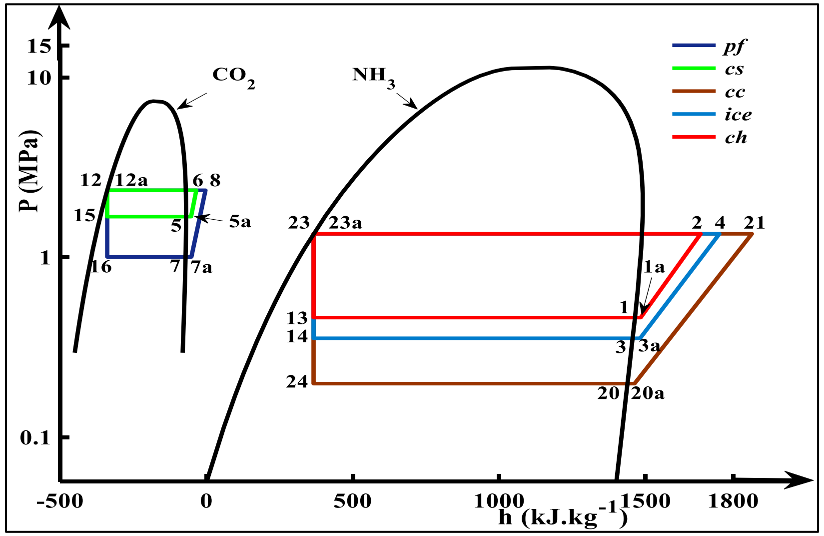
a) Baseline refrigeration system



c) Cascade refrigeration system

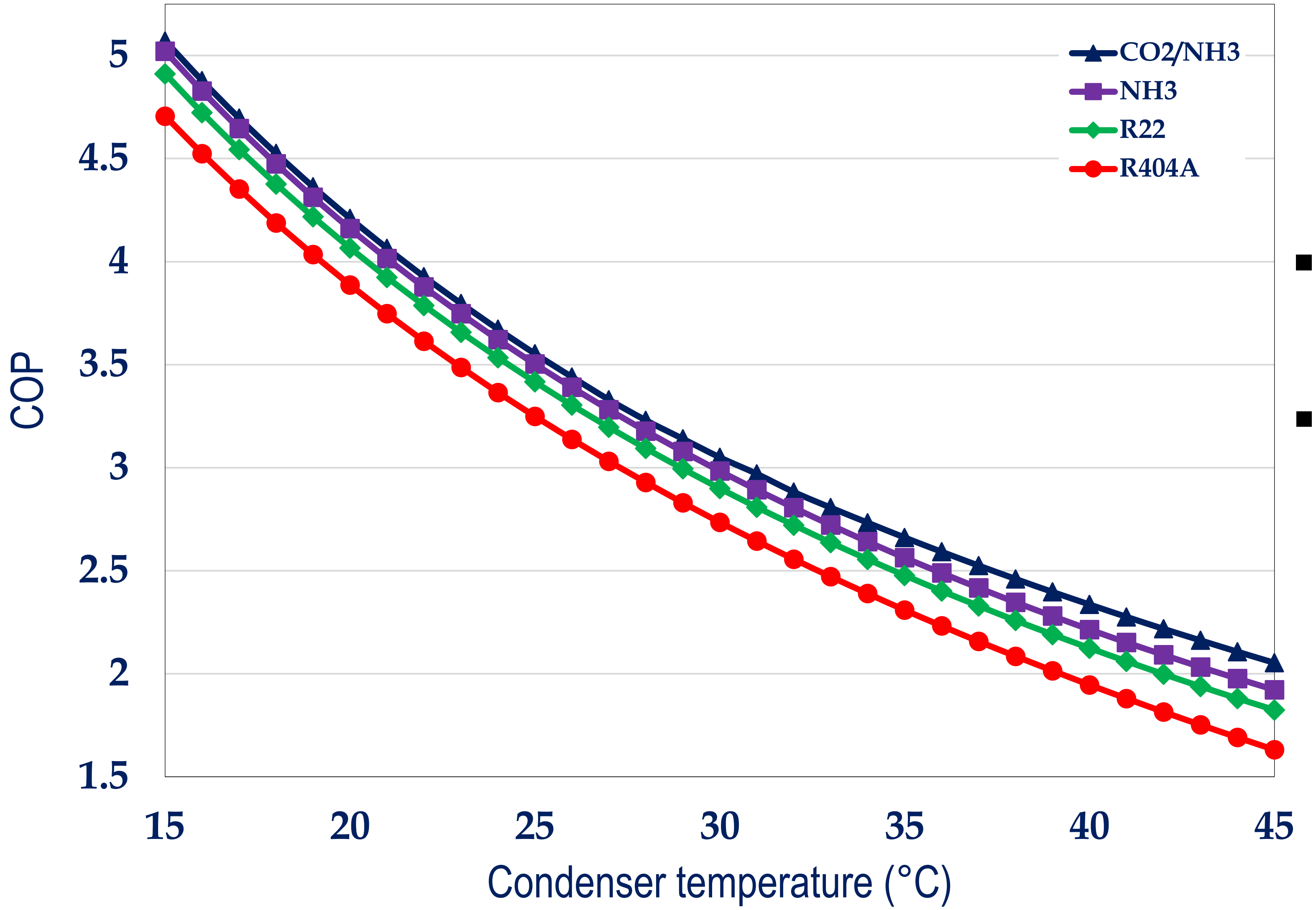


b) Baseline P-h diagram



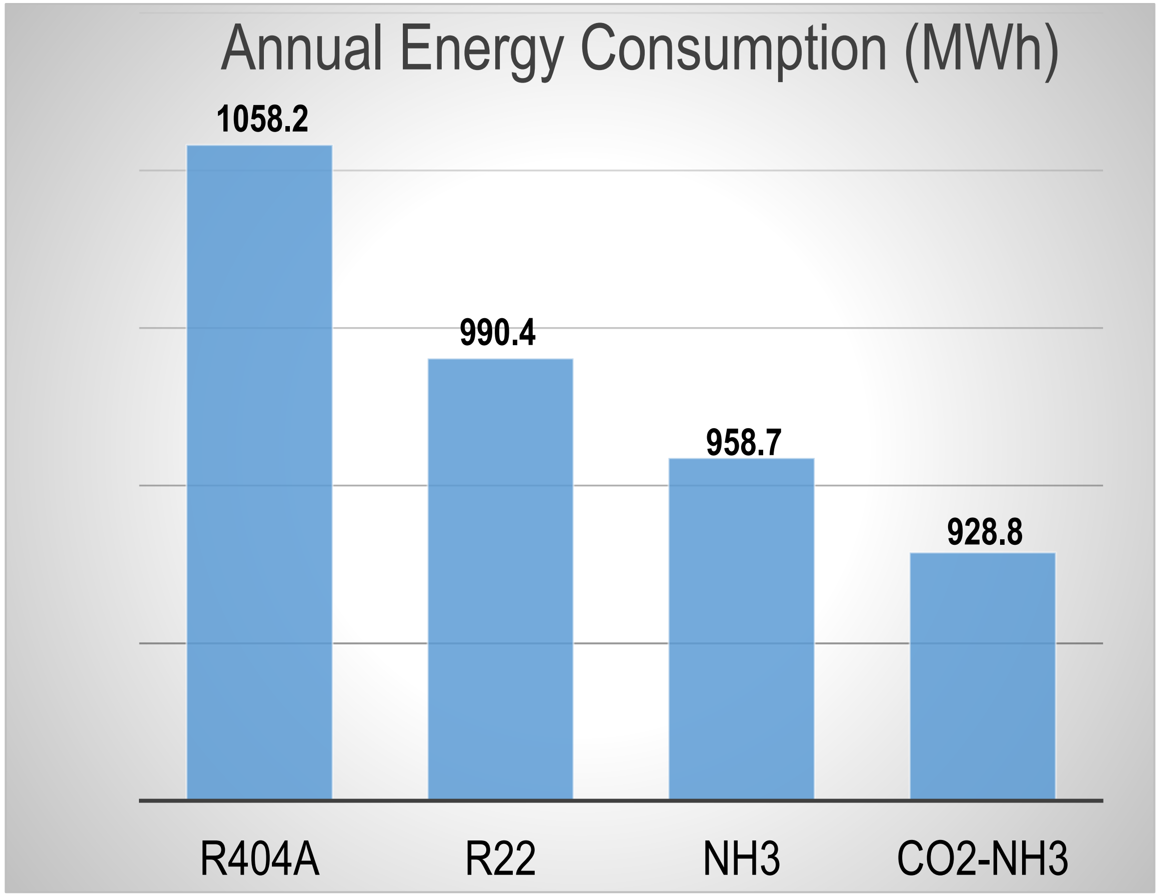
d) CRS P-h diagram

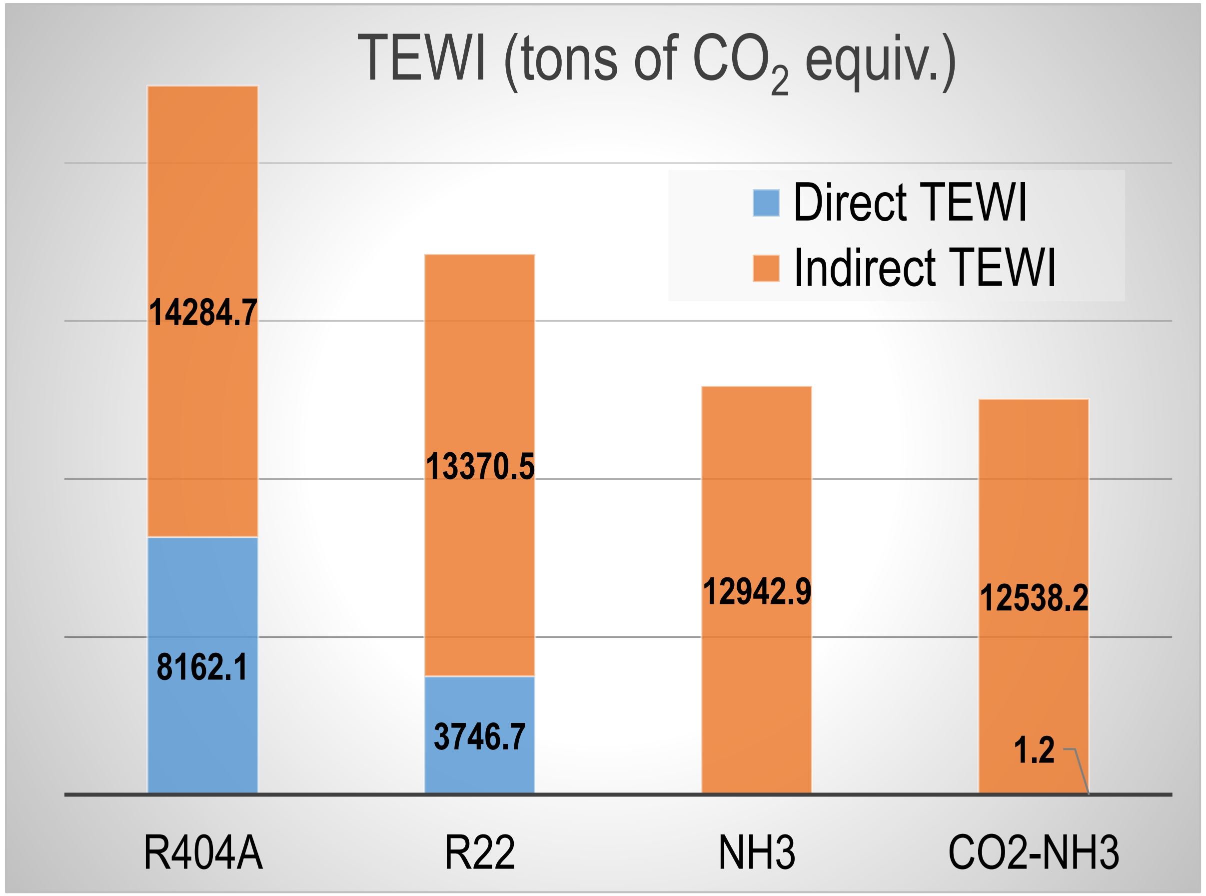
Performance Comparison



- CO_2-NH_3 CRS has the highest COP, R404A in two-stage has the lowest
- Difference in COP: more pronounced at higher ambient temperatures

Performance Comparison





- CO_2-NH_3 CRS has the lowest AEC, 12.3% less compared to R404 2-stage VCR,
- Save ₹ 10.35 L ($14278) annually
- CRS has the lowest TEWI too, 44.3%, 26.8% & 3.2% less compared to R404A, R22 & NH3 2-stage VCR

Why CO_2-NH_3 CRS?

Mostly studied refrigerant pair for low temp applications | 20 out of 42 studies since 2005 in CRS refrigerant pairs (Aktemur et al., 2020)

CO_2

- High liquid/vapor density (more pronounced at lower temp.)
- high volumetric refrigeration capacity
- low compression ratio
- lower NBP temperature
- Non-toxic, non-flammable A1 safety group, safer
- Compact system
- Smaller compressor displacement at low temp
- Thermally efficient copper pipes in heat exchangers

- Low critical temp & high critical pressure
- Limited skilled labour
- High component cost
- Absence of local manufacturer

NH_3

- High latent heat of vaporization, 6-8 times others (at 0 ºC)
- Well-established refrigerant large industry
- Negligible environmental impacts
- well skilled labour
- local component manufacturers
- easy leak detection

- Lower density, large component size, material compatibility issues
- Toxicity and flammability (B2L)
- Regulatory restrictions
- Food contamination potential

Aktemur, C., Ozturk, I. T., & Cimsit, C. (2020). Comparative energy and exergy analysis of a subcritical cascade refrigeration system using low global warming potential refrigerants. ATE.

Conclusion

- Increasing seafood demand and production, more cold chain infrastructure to overcome food waste issues
- Increasing energy demand for cooling and various restriction policies to reduce environmental impact forcing use of environmentally benign refrigerants
- Proposed system uses natural refrigerants, having negligible direct and lesser indirect environmental impacts
- Improved thermodynamic performance
- Other benefits
  - Reduction in number of compressors, pressure ratio in compression, total NH_3 charge
  - Possible isolation of NH_3 from food

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ReValue: Innovative technologies for improving resource utilization in the Indo-European fish value chains

Thanks much for your attention