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Subash, Abhirami; Ramanathan, Hareesh N.; Šostar, Marko

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Article

Market-Driven Mapping of Technological Advancements in the Seafood Industry: A Country-Level Analysis

Abhirami Subash [1], Hareesh N. Ramanathan [1] and Marko Šostar [2,*]

[1] School of Industrial Fisheries, Cochin University of Science and Technology, Fine Arts Avenue, Kochi 682016, India; abhiramisubash@cusat.ac.in (A.S.); hareeshramanathan@cusat.ac.in (H.N.R.)
[2] Faculty of Tourism and Rural Development in Pozega, Josip Juraj University in Osijek, Vukovarska 17, 31000 Pozega, Croatia
* Correspondence: msostar@ftrr.hr

Abstract: Seafood preservation techniques have evolved from ancient methods to modern innovations like canning, freezing, and surimi production. Canning in the 19th century introduced airtight containers, while commercial freezing technologies like flash freezing extended shelf life. Surimi pastes in the 20th century led to affordable imitation seafood products. Emerging technologies continue to enhance seafood preservation methods. Moreover, the integration of digital technology, automation, and data sharing, known as Industry 4.0, is transforming various industries. This integration encompasses blockchain technology, automation, robotics, and big data analytics, aiming to enhance production, sustainability, traceability, and efficiency in fish processing. With a focus on the seafood market dynamics affecting these advances, this research was conducted with the aim to understand how technical breakthroughs in the seafood business are dispersed and implemented across different nations. We aim to determine the correspondence between the technological sophistication of machinery in seafood processing companies and map it across different countries across the globe to obtain an understanding of the generation of technology used in prominence. Variations in adoption rates and technological trends reflect regional market dynamics. The Seafood Expo ASIA 2023 study looked at the use of Industry 4.0 technologies, operational procedures, and technology adoption in the global seafood processing industry. Notably, countries like Norway, the Republic of Korea, Spain, Turkey, and the Netherlands have rapidly embraced Industry 4.0 technologies. The market factors driving these technological advancements across different countries include rising consumer demand for sustainable seafood, economic incentives, and global competition. A correspondence analysis was employed to analyze the correspondence between countries and the level of technological sophistication in the machinery used. We successfully mapped the level of technology utilized in machinery across global seafood processing companies, providing insights into the technological advancements shaping the industry.

Keywords: technological innovations; Industry 4.0; seafood processing; technology advancement; Seafood Expo ASIA 2023; technology generation; seafood market

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1. Introduction

A regular and important occurrence for a nation's economic progress in a market economy is competition. In the seafood industry, competition has long existed, and theories of competition, including the classical and contemporary theories of competition, were among the first to be developed (Tran 2020). The seafood business plays a vital role in the global economy by giving millions of people access to food, jobs, and money (Fox et al. 2018). Due to globalization, which has caused major multinational corporations to consolidate and integrate vertically throughout supply chains, from manufacturing to sale, seafood is one of the foods that is traded most often worldwide (Bellmann et al. 2016; Gephart and Pace 2015). The major challenges faced by food business are getting the food market to identify and accept new meals made from intercropping crops (Mamine and Farès 2020), which are indeed similar to the challenges of the seafood industry regarding bringing up easy cooking and handling products (Ha et al. 2024). A large and growing body of scientific research has documented the benefits of seafood in the human diet (Campos and Qi 2024)

The seafood processing industry employs approximately 56 million people worldwide and brings in over USD 200 billion in sales yearly (FAO 2020). Seafood supply chains often consist of many nodes, representing a distinct production or distribution to the company. Before the final sale, different nodes in the processing section process and fuse products to different degrees (Virdin et al. 2022). Policy discussions often touch on the share of domestic food goods in retail, aiming to promote value-added products and job opportunities and leading to rural development, which is a significant factor for the fisheries sector. The preservation of local food tradition, which is frequently linked to national security, sustainability, and the local economy, is another highlighting feature of seafood (Kasza et al. 2024).

Over the past 60 years, there have been significant technical breakthroughs in fish post-harvest technology, including increased quality control, fish preservation, processing, packing, and processing technology (Majumder and Balange 2023). The loss of this nutrient-rich food product is detrimental to a country with a high undernutrition rate (Graham et al. 2007). To mitigate this loss, improved handling and processing, as well as preservation methods, must be used. Therefore, it is crucial to develop the fishing industry as such in light of all worldwide needs.

1.1. Seafood Processing

The seafood industry plays a crucial role in the global food supply chain. To adapt to the different interests of consumers, seafood enterprises need to engage in specialized activities such as harvesting, processing, distribution, and marketing. These corporations manage complicated natural and commercial ecosystems to acquire and market a diverse range of aquatic goods in a sustainable manner. Seafood companies strive to supply high-quality seafood to customers all around the world by concentrating on quality and nutritional content.

Seafood is a great source of protein, vitamins, minerals (particularly iron, iodine, calcium, and potassium), and polyunsaturated fatty acids. When ingested, they have been shown to protect against many illnesses, including cancer, high blood pressure, inflammatory and cardiovascular disorders, and more (Kathuria et al. 2022). The traditional seafood-processing sector has faced challenges due to the perishable nature of seafood. Modernistic approaches in food science and technology are, however, affording innovative ways by which these challenges can be surmounted. By focusing on the improvement in seafood quality, the extension of shelf life, and ensuring its safety, the industry would increase its competitiveness level as well as meet the increasing demand for high-quality seafood products (Russo et al. 2023). Although there have been significant breakthroughs in the procedures used for food safety testing, several issues still exist (Virdin et al. 2022). For instance, commonly used biosensor technologies have the benefits of low specificity, cheap cost, and real-time detection; yet their specificity is still poor (Cheng et al. 2023). Quality assurance is a major concern in the seafood processing industry, as the retention of consumer confidence and regulatory requirements for quality exist. Precise labeling and certification are two important tools to communicate product quality attributes effectively to customers, showing compliance with industry standards (Yasuda and Bowen 2006). The seafood sector is subject to mandatory control measures, such as Hazard Analysis Critical Control Points (HACCP) systems, as well as federal and state rules affecting harvest techniques and traceability standards (Jensen 2006). New Approach Methodologies (NAM) have begun to win fame for the toxicological testing methodologies that can be used as an alternative, especially in the pharmaceuticals, cosmetics, food, and seafood industries. Furthermore, interest in the regulatory use of NAMs will remain high, mainly due to their wider applicability and the potential reduction in animal testing (Manful et al. 2023).

The study of seafood microbiota has undergone a revolution owing to high-throughput sequencing (HTS) technology, which offers a better representative picture of the microbial populations in seafood ecosystems (Rönnbäck 1999). New prevalent bacteria in seafood have been identified through this technique, including psychrobacter, which was found to be a significant cause of seafood spoilage (Anagnostopoulos et al. 2022).

The challenges facing seafood processing in the supply chain for product safety and quality are massive: proliferating labels, complexities in regulation, quality assurance standards, intricacies in labeling, market fluctuations, and certification requirements (Caswell 2006). In the processing sector, the key components of quality control include Good Manufacturing Practice (GMP), Hazard Analysis and Critical Control Point (HACCP), sensory assessment methodologies, and traceability systems (Alam 2007). The need for a paradigm changes in the guarantee of seafood safety, difficulties in monitoring and identifying chemical pollutants in the seafood chain, and the application of HACCP systems is required (Eguiraun et al. 2015).

The world's population is anticipated to reach 10 billion by 2050 (FAO 2022). The seafood industry, particularly in Asia, is crucial to global food supply chains. However, it needs help with traceability and transparency. Despite improvements in traceability practices, information flow and governance still need to be improved. A wide variation in technology adoption was observed by Peng et al. (2020), with some companies adopting innovative technologies for traceability, making it faster, more reliable, and more cost-effective. These advanced technologies have enabled accurate data capture, improved supply chain management, and improved business performance. Despite significant advances in robotization and automation, IR 4.0 technologies are often unable to be fully implemented in the seafood industry due to biological variations in raw materials, seasonal production, and the varied distribution of catch and procurement (Hassoun et al. 2022). Following processing practices, including maintenance at a low temperature, the specific needs to wash and disinfect surfaces should also be carried out on a large scale with hygienic disinfection. Economic viability due to the high costs of these technological processes is also a major challenge that needs to be tackled (Echegaray et al. 2022). Seafood waste management, the sustainable use of byproducts from seafood processing, and the significance of marine-acquired biomolecules in agriculture, biotechnology, and the food sectors are all important spheres to consider (Akhila et al. 2024). Jiao et al. (2024) emphasized the need for a green processing transformation, specifically in the traditional surimi-based industry due to their high pollution and energy consumption, with microwave processing, which is identified as an effective method to promote the green manufacturing of surimi-based products. The Industrial Revolution has been a continuous process of technological advancements and improvements in various sectors. Before Industry 4.0, three industrial revolutions (IR) occurred: IR 1.0 in the late 18th century, which transitioned from manual to mechanized work and production powered by steam; IR 2.0 in the early 1970s, which introduced the use of electrical power for mass production; and IR 3.0 in the late 19th century, which introduced electronics and information technology, leading to automated production. These revolutions have significantly impacted various sectors and continue to evolve with time and needs (Lin et al. 2018). Through the use of intelligent sensors and actuators, Industry 4.0 seeks to increase manufacturing efficiency and communication while concentrating on customer centricity and new business prospects (Grabowska 2018). The scopes and directions for implementing technologies in Industry 4.0 architectures have also stated the importance of IR 4 (Rane and Shah 2022). Industry 4.0 technologies contribute to sustainability functions, such as risk and safety management, by providing chances for greater production efficiency, manufacturing cost reduction, and environmental responsibility development (Ghobakhloo 2020). Thus, these technologies promote energy and resource sustainability by enabling the reduction in energy use and waste through data analysis across industrial and supply chain processes (Bai et al. 2020).

This study explores the technological sophistication of machinery in seafood processing across different countries using correspondence analysis. It links market dynamics to technological adoption, highlighting the influences of consumer demand, economic incentives, and global competition. The research focuses on Industry 4.0 technologies in a specific sector, blockchain, automation, robotics, and big data analytics. It also provides a cross-country comparative analysis, revealing why some countries, like Norway and Korea, are leading in adoption, while others are slowing down. This study contributes to food technology, industrial innovation, and economic development.

1.2. Industry 4.0

Industry 4.0 is an interdisciplinary strategy that combines the physical, digital, and biological worlds. Industry 4.0 technologies in agriculture and food include AI, IoT, smart sensors, robotics, and 3D printing (Hassoun et al. 2022). Artificial intelligence and blockchain are two 4.0 technologies that can significantly improve the traceability of systems in the seafood processing sector. These technologies make traceability procedures more efficient, accurate, and secure. The development of wholly new knowledge or the application of already-existing technology are the two ways that technological advancement is accomplished. The degree of human capital in a nation determines whether new technology is successfully invented or if old technology is absorbed (Dao and Khuc 2023). The transition to a Circular Economy and Industry 4.0 is both a promising and demanding topic to study. Furthermore, these technologies enable real-time data collection and processing, resulting in prompt detection and response to possible food safety hazards (Bertossi 2024). In this paper (Martini et al. 2023), the authors investigate the key drivers of digital innovation within micro and small industries (MSIs) in Indonesia, focusing on the role of internet adoption and usage levels. The analysis considers a range of factors, including business and marketing strategies, operational constraints, access to credit, and both entrepreneurial and firm-specific characteristics. The goal is to identify how these elements collectively influence the digital transformation of these industries. Industry 4.0 also plays a vital role in other areas, contributing to the industrial revolution. Conventional approaches have limits, whereas vision-based technologies allow for the rapid and non-destructive examination of food composition and nutritional content compilation (Kaushal et al. 2024). Using these modern technologies, seafood processing enterprises can achieve end-to-end traceability, from raw material source to final product on shop shelves (Echegaray et al. 2022).

Renewable sources of energy and decentralized energy concepts will play a crucial role in supply chain management in the coming generations (Fleiß et al. 2024). In the Fourth Industrial Revolution, disruptive technologies like blockchain and cloud computing are anticipated to transform data storage, security, and applications with a focus on the extensive use of digital technologies in manufacturing, therefore affecting several businesses (Papakostas et al. 2020). Blockchain technology can improve financial transactions, supply networks, and medical data security and transparency. Cloud computing allows companies to grow profitably, cut expenses, and improve teamwork by facilitating remote work. These technologies are projected to revolutionize sectors by promoting innovation, enhancing data management, and simplifying procedures (Rahman et al. 2017).

Supply chain management, environmental considerations, information and technology integration, corporate culture, and social responsibility are some critical facilitators of sustainability in Industry 4.0 in emerging economies. These enablers can be applied by adopting technology, training personnels on sustainable practices, forming partnerships with suppliers to promote sustainable sourcing, and incorporating environmental management systems into operations. Additionally, raising knowledge about the benefits of sustainability and rewarding sustainable practices can help encourage the adoption of these enablers in emerging economies (Jamwal et al. 2021).

2. Methodology

The survey approach was used in the study to collect data, with an emphasis on the Seafood Expo ASIA 2023 show. Exhibitions are essential venues for industry participants to meet, share knowledge, and present their newest goods and services. An excellent venue for gathering data was provided by the Seafood Expo ASIA, a major event in the seafood sector that drew a sizable number of participants from various businesses.

The study went through a descriptive research design, aiming to identify the degree of technology of both the seafood processing machines and processing methods in each country with respect to the raw materials processed and the level of marketing competence. Primary data on the technology level of machines were attained by means of a survey method, and a correspondence analysis was used for data analysis. Correspondence analysis is a statistical method for visualizing and examining the connections between categorical variables in a contingency table. Converting complicated and huge data into a lower-dimensional space makes patterns and structures visible and simplifies the data. The resultant graphic illustrates how closely related categories have stronger associations and are more comparable to one another (Kurian et al. 2022).

A total of 505 companies registered in the Seafood Expo ASIA 2023 (as mentioned in Table 1), which serves as the sample frame. The Seafood Expo ASIA 2023, held in Singapore from September 11 to 13, provided a valuable opportunity to collect 338 responses from companies. The questionnaire was developed with the help of literature surveys and pilot studies conducted in the seafood industry. It comprised four segments which included questions on the raw materials processed in the company, the type of raw material processing, the current generation of the machines used in the processing section, and the trading details of the company. Companies were segregated and selected according to the criteria derived from the questionnaire, as mentioned in Table 2, to study their work atmosphere and market. Each stall at the Seafood Expo Asia 2023 was individually attended, and basic data were recorded.

Table 1. Country/region and company details.

SL NO.	COUNTRIES/REGIONS	TOTAL COMPANIES
1.	ARGENTINA	8
2.	AUSTRALIA	23
3.	BAHRAIN	1
4.	BANGLADESH	1
5.	BRUNEI DARUSSALAM	1
6.	CANADA	15
7.	CHILE	2
8.	CHINA	47
9.	ECUADOR	8
10.	FALKLAND ISLANDS	1
11.	FAROE ISLANDS	1
12.	FIJI	1
13.	FRANCE	5
14.	GEORGIA	1
15.	GREECE	1
16.	HONG KONG	4
17.	INDIA	10
18.	INDONESIA	1
19.	JAPAN	10
20.	KIRIBATI	1
21.	MALAYSIA	2

Table 1. *Cont.*

SL NO.	COUNTRIES/REGIONS	TOTAL COMPANIES
22.	MAURITANIA	1
23.	MAURITIUS	1
24.	NETHERLANDS	11
25.	NEW ZEALAND	3
26.	NICARAGUA	1
27.	NORWAY	15
28.	OMAN	1
29.	POLAND	9
30.	REPUBLIC OF KOREA	10
31.	SINGAPORE	30
32.	SOLOMON ISLANDS	2
33.	SPAIN	9
34.	SWEDEN	1
35.	TAIWAN	10
36.	TURKEY	10
37.	UNITED KINGDOM	2
38.	UNITED STATES	13
39.	VIETNAM	26
40.	YEMEN	5

Note: This Table shows the details collected from the Seafood Expo Asia 2023.

Table 2. Criteria for selection.

	Categorizations were based on questionnaire content
Major companies (excluding absent/daughter companies)	1. Processing methods: pre-processing, processing, and packaging.
	2. Raw materials: fin fish, crustaceans, mollusks, and others.
	3. Trading.

Note: From the participation list of 505 companies, 338 companies were selected under the above-mentioned conditions.

Not all companies attended the expo, and some major companies exhibited multiple stalls representing small counter divisions. Hence, these constraints led to a decrease in responses concerning the criteria in Table 2.

The data included 338 entries, collected from 40 countries/regions that participated in the Seafood Expo Asia 2023, which were analyzed using correspondence analysis. Correspondence analysis uses a two-dimensional correspondence table to describe the connections between two nominal variables, as well as the categories associated with each variable. With regard to the data under investigation, the nominal variables are country and technology levels, respectively. Technological levels in the seafood processing machines categorized based on processing techniques are illustrated in Table 3. The correspondence analysis conducted clearly shows the relation of the machines in the seafood industry at different sections with technology classification at the latest 3 levels of generation.

Table 3. Generation classification.

The First Industrial Revolution denotes the first generation	Traditional practices include salting, sun drying, pit curing, etc.
The Secondary Industrial Revolution denotes the second generation.	Basic freezing machines, metal detecting machines, plate freezers, canning, etc.
The Third Industrial Revolution denotes the third generation.	A step ahead of the basic machines, with modifications, systematic controllers for freezing, IQF, value addition, etc.
The Fourth Industrial Revolution denotes the fourth generation.	Sensor applications, fingerprint-controlled machines, big data storage, automatic machines in applications, etc.

Note: This table consists of the criteria based on which the companies were classified according to the technological advancements.

3. Result and Discussion

Each country was assessed in terms of the level of technology of its seafood processing machines and methods, focusing on raw material categorization and the level of commerce. A survey was utilized to collect responses from 338 companies who indeed participated in the Seafood Expo ASIA 2023 in Singapore. The sample frame included 505 companies from 40 Asian countries/regions. The results show a strong correlation between the level of technology used and the seafood industry's ability to process, trade, and store its products. Companies with higher levels of technology were better able to adapt to changing market conditions and customer demand. The study concluded that the level of technology in seafood processing is a key factor in the success of the seafood industry.

Table 4 clearly illustrates the number of seafood enterprises from various nations based on technology generation. The bulk of the firms who participated in the seafood exhibition were from China, with a total of 111 corporate representatives, with just four enterprises falling into the fourth generation of technology. China also ranks top in the number of enterprises that fall into the third generation of technology, with 71 companies on the list. Vietnam, with a total of 40 companies, was the next country with the majority of firms (20) falling into the third generation and 9 companies falling into fourth-generation technology. When compared to the active margin of just eight companies, the total participants representing Norway showed a lead of six companies falling into the fourth-generation level of technology. Norway's seafood processing companies appear to have adopted sector 4.0 to a great degree, as evidenced by the country's predominance of fourth-generation technology.

Table 4. Correspondence table. Country-wise division of companies that fall into different categories of technology according to generation.

Country/Region	Technology			
	2nd Generation	3rd Generation	4th Generation	Active Margin
Argentina	1	4	0	5
Australia	4	14	0	18
Bahrain	0	0	0	0
Bangladesh	0	2	0	2
Brunei Darussalam	0	2	0	2
Canada	0	4	0	4
Chile	0	3	0	3
China	36	71	4	111
Ecuador	2	0	0	2
Japan	0	9	0	9

Table 4. *Cont.*

Country/Region	Technology			
	2nd Generation	3rd Generation	4th Generation	Active Margin
Faroe Islands	0	2	0	2
Fiji	0	0	0	0
France	0	7	0	7
Georgia	0	0	0	0
Greece	0	1	0	1
Hong Kong	0	1	0	1
India	7	2	2	11
Indonesia	4	1	0	5
Kiribati	0	0	0	0
Malaysia	3	0	0	3
Mauritania	5	0	0	5
Mauritius	0	0	0	0
Netherlands	0	8	5	13
New Zealand	0	3	0	3
Nicaragua	2	0	0	2
Norway	0	2	6	8
Oman	0	0	0	0
Poland	2	5	0	7
Republic of Korea	1	2	3	6
Singapore	1	13	3	17
Solomon Islands	0	0	0	0
Spain	3	2	3	8
Sweden	0	0	0	0
Taiwan	0	17	0	17
Turkey	0	1	1	2
United Kingdom	0	0	0	0
United States	6	3	0	9
Vietnam	11	20	9	40
Yemen	0	15	0	15
Active Margin	88	214	36	338

Figures 1–3 show how the degrees of technology in different nations are compared graphically. The clusters or groupings of nations with comparable technical characteristics, depicted in the image, help explain the links between nations and technological generations.

The variables in the figure were transformed into a two-way contingency table using row variables, column variables, and supplemental variables. The row variables represent the participating countries/regions, while the column variables represent the level of generations concerning the technology. Figure 2 illustrates a comparison of the level of technology in the country. It is evident that a group of countries, including China, Australia, Poland, Argentina, Chile, India, the United States, etc., concentrate on the third generation, whereas Norway stays at the peak, indicating fourth-generation technology, with surrounding countries like the Republic of Korea, the Netherlands, and Spain below it.

Another similar cluster is seen around the second generation of countries, including New Zealand, Mauritania, Malaysia, Indonesia, Ecuador, etc.

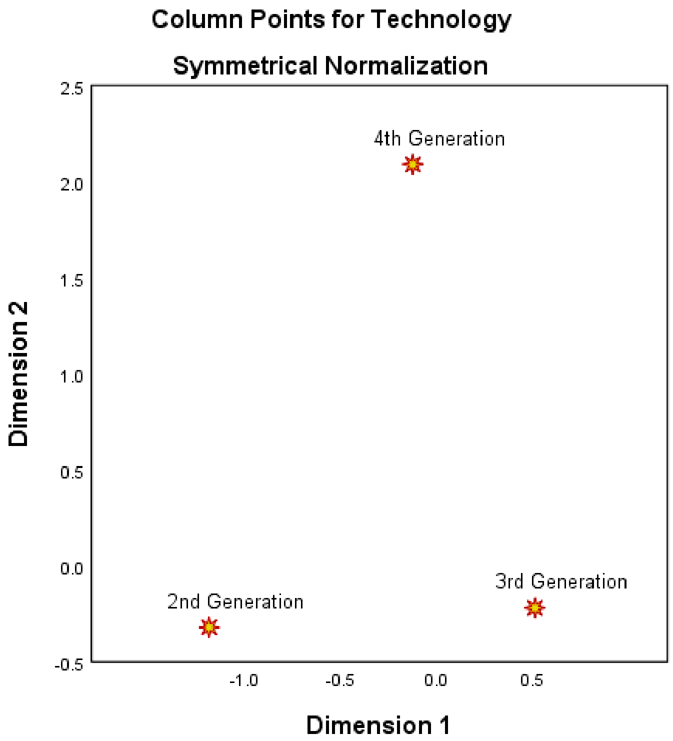

Figure 1. Column points denoting technology.

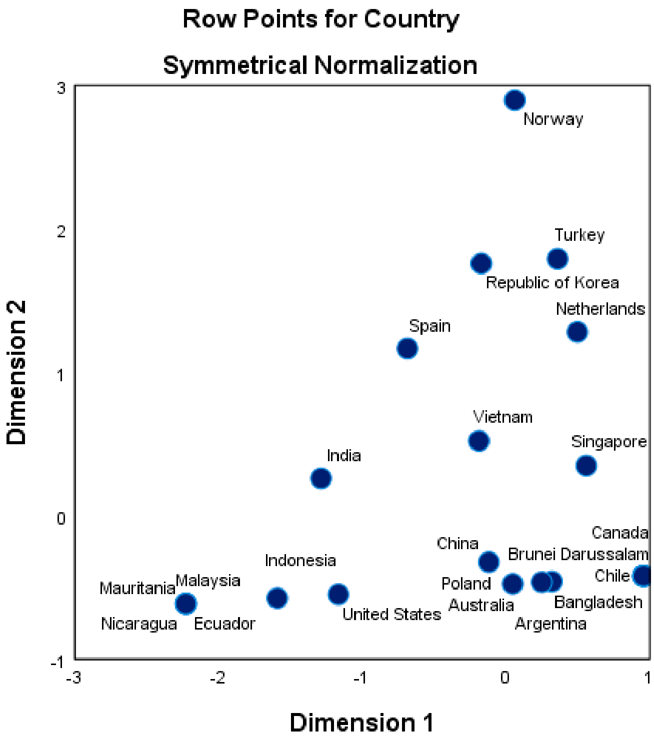

Figure 2. Row points denoting countries.

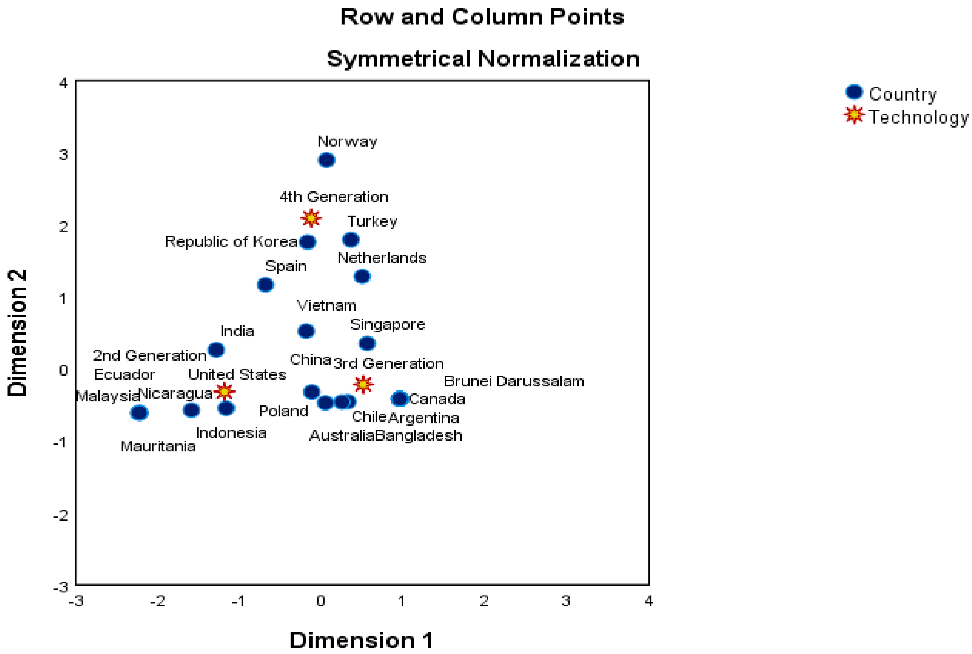

Figure 3. Row and column points. Note: Figures 1–3 display the spatial maps of seafood companies participating in the Asian Seafood Expo ASIA 2023.

In Figures 1 and 2, the arrangement shows a hand-in-hand relation as it brings the row as well as the column components together. From Figure 3, we can conclude that there is a clear relationship and dependence on the level of technology and seafood processing companies globally. Hence, the test result is significant as shown. In order to fully comprehend how technology has impacted the seafood sector and how innovations are advancing sustainability, efficiency, and quality in seafood processing, we conducted a thorough historical overview of the development of preservation techniques and the integration of cutting-edge technologies.

According to the current report, the global seafood processing sector is at a tipping point in terms of technical advancement. This growth is attributed to the widespread use of Industry 4.0 technologies such as user-friendly equipment, blockchains, automation, robots, and big data analytics. The study presented in (Johansen et al. 2019) focuses on the importance of high-quality seafood products for economic sustainability, the role of manufacturing in food innovation, and public concern over seafood security within the context of Industry 4.0 and the Sustainable Development Goals. This modern era of technological perspective has changed seafood production to be much more productive, sustainable, traceable, and effective. With the help of Industry 4.0, the seafood industry will be able to maintain competitiveness within the international market and solve major issues in resource management and environmental challenges. The seafood industries worldwide have differences and changes when each single company is taken into consideration.

Figure 3 describes the clarity of each country in each section of technology practiced and followed, respectively.

4. Limitations and Future Research

This study on the technological landscape of the seafood processing industry has several limitations. This study's representation of companies was uneven, leading to potential biases in the analysis of technological sophistication. The level of technology sophistication in companies' machinery and processes was estimated through direct observation and informal interactions with company officials, potentially resulting in subjective or incomplete data. The event's focus on trade and promotion may not have fully showcased technological capabilities, potentially masking the true extent of advancements. Additionally, not all products and machinery were exhibited at the expo, posing a challenge in assessing the full range of technologies in use.

Regarding the results of this study, more research is required in a number of important areas. In the future, the seafood sector will likely pursue technological innovation in deeper ways, such as via adopting sophisticated automation, robots, and AI-driven processes for efficiency and quality control. Additionally, there is a need to look at the less explored aspects of Industry 4.0 in seafood processing, such the application of IoT-enabled monitoring systems for real-time data collection and the integration of blockchains for supply chain transparency and traceability. To promote the adoption of Industry 4.0, governments should offer clear policies, incentives, and subsidies. For businesses investing in these technologies, governments may provide tax rebates, subsidies, or low-interest loans. Creating innovation hubs can facilitate communication between entrepreneurs and industry participants. High upfront costs, a shortage of experienced workers, inadequate infrastructure, and erratic rules are some of the barriers to adoption. To guarantee the success of Industry 4.0 in seafood processing, governments must back these initiatives. Blockchains, AI, automation, and smart factories are some of the upcoming innovations in seafood processing. Governments should offer clear policies, incentives, and subsidies to encourage Industry 4.0 adoption in seafood processing, overcoming obstacles like high initial investments, skilled labor shortages, infrastructure deficiencies, and inconsistent regulations.

Further research is also necessary to identify the obstacles to technology adoption, especially in developing nations, and to design policies and tactics that are specifically suited for businesses and legislators. These research focuses will assist in establishing this study as a cornerstone for future developments in the field of seafood processing technology. Future research could provide a more comprehensive understanding of the technological landscape.

5. Conclusions

The necessity for sustainable practices, globalization, and changes in customer tastes have all had a significant impact on the seafood processing industry's technological improvements. By virtue of advancements in technology, packaging, logistics, and transportation, as well as shifting customer preferences, the business has expanded into high-value fresh and processed goods. The intensification, geographical concentration, vertical integration, and integration with global supply chains in the seafood processing industry have increased, which is indicative of the growing globalization of the value chain in fisheries and the expansion of worldwide distribution channels under the control of major merchants.

The seafood processing industry all over the world is at a pinnacle in technological changes according to the present study. Such development is due to the huge use of Industry 4.0 technologies, which include user-friendly equipment, blockchains, automation, robotics, and big data analytics. This modern era of technological perspective has changed seafood production to be much more productive, sustainable, traceable, and effective. With the help of Industry 4.0, the seafood industry will be able to maintain competitiveness within the international market and solve major issues in resource management and environmental challenges. This emphasizes the significance of ongoing investment in technology and innovation within the seafood industry to drive growth and meet evolving consumer demands.

Industry 4.0 technologies often face barriers in adoption, including high initial costs, a shortage of skilled workforce, infrastructure limitations, limited access to technology and support networks, regulatory and policy constraints, and concerns about return on investment. Smaller companies in developing regions often lack the capital or access to affordable financing to adopt these technologies, limiting their ability to compete with larger, more financially robust companies. Another significant obstacle is the availability, acquisition, and handling of newly accessible raw materials for production. Regulatory and policy constraints, as well as uncertainties about the return on investment, further exacerbate the technological gap between developed and developing regions.

The Seafood Expo ASIA 2023 study (from Table 5) examined the use of Industry 4.0 technologies, operational procedures, and technology adoption in the worldwide seafood processing sector. Norway, the Republic of Korea, Spain, Turkey, the Netherlands, and other significant nations have all embraced Industry 4.0 technology, as seen in Figure 3 and Tables 4 and 6. In contrast to other industries like software, the chemical industry, and even the food industry, the seafood industry has only recently reached the second level of technological development. This is demonstrated by the fact that not a single seafood company that took part in the Expo used first-generation technology. This trend clearly shows that even the least technologically sophisticated processes have been replaced in all industries, including the seafood industry. The fast speed of technology innovation, along with rising expectations for efficiency and sustainability, has compelled businesses to use increasingly modern systems. This development indicates the industry's resolve to remain competitive and satisfy global standards since obsolete technology no longer suffices in managing new difficulties.

Table 5. Correspondence analysis summary.

Dimension	Singular Value	Inertia	Chi-Square	Sig.	Proportion of Inertia		Confidence Singular Value	
					Accounted for	Cumulative	Standard Deviation	Correlation 2
1	0.533	0.284			0.510	0.510	0.035	0.010
2	0.522	0.273			0.490	1.000	0.060	
Total		0.557	188.309	0.000 [a]	1.000	1.000		

78 degrees of freedom, [a]: below 0.005 is significant. Note: summary.

Table 6. Technology-wise distribution of countries as per the analysis.

TECHNOLOGY CLASSIFICATION	COUNTRIES FALLING INTO THE CATEGORY
The Secondary Industrial Revolution denotes the second generation.	Ecuador
	Indonesia
	Nicaragua
	Malaysia
	Mauritania
The Third Industrial Revolution denotes the third generation.	United States
	Singapore
	China
	India
	Canada
	Chile
	Brunei Darussalam
	Argentina
	Australia
	Vietnam
	Bangladesh
The Fourth Industrial Revolution denotes the fourth generation.	Norway
	Republic of Korea
	Spain
	Turkey
	Netherlands

Note: Interpretation of correspondence analysis results.

The fast deterioration of seafood items has been addressed in large part by major technical breakthroughs in quality control, preservation, and packaging. Blockchain, artificial intelligence, the Internet of Things, smart sensors, robots, and other Industry 4.0 technologies have significantly improved supply chain management, traceability, and food safety. However, because of things like biological variances in raw materials, the necessity for specialized surface cleaning and disinfection requirements, and economic feasibility, the use of these technologies varies greatly throughout firms. The adoption of innovative technical processes is sometimes limited by their high cost, especially by smaller enterprises, which resembles a hurdle that needs to be tackled.

With improved waste management, the sustainable use of byproducts, and the use of green processing technology, sustainability and environmental effects are becoming more significant in this sector. Future supply chain management must incorporate decentralized energy concepts and renewable energy sources to foster environmental responsibility. Recommendations for augmenting the industry's advancement encompass motivating technological investment, fortifying regulatory structures, endorsing eco-friendly methodologies, improving training and instruction, and cultivating cooperation and information exchange. Industry 4.0 presents possibilities and difficulties that must be met if the sector is to grow, prosper, and make a substantial contribution to both economic growth and global food security.

In summary, this study successfully mapped the level of technological sophistication of the equipment utilized by seafood processing enterprises in different nations. The study's use of correspondence analysis yielded insightful information about how technology innovations are distributed and applied in the seafood sector. In addition to providing a thorough picture of how technological advancements are influencing the global seafood sector, the findings also emphasize the role that Industry 4.0 and new technologies play in improving production, sustainability, traceability, and efficiency. Future industry investments and policy choices can be referred by this knowledge to enhance the market in the seafood sector.

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Abbreviations

NAM	New Approach Methodologies
HTS	High-Throughput Sequencing
HACCP	Hazard Analysis Critical Control Points
GMP	Good Manufacturing Practice
IR	Industrial Revolution
AI	Artificial Intelligence
IoT	Internet of Things

References

Akhila, D. S., Priyanka Ashwath, Kavitha Guladahalli Manjunatha, Sadanand Dangari Akshay, Vijay Kumar Reddy Surasani, Faisal Rashid Sofi, Kawkabul Saba, Pavan Kumar Dara, Yesim Ozogul, and Fatih Ozogul. 2024. Seafood processing waste as a source of functional components: Extraction and applications for various food and non-food systems. *Trends in Food Science & Technology* 145: 104348. [CrossRef]

Alam, Nowsad. 2007. Quality Control of Fish. *ResearchGate* 17: 288–305. Available online: https://www.researchgate.net/publication/342232039 (accessed on 17 June 2007).

Anagnostopoulos, Dimitrios A., Foteini F. Parlapani, and Ioannis S. Boziaris. 2022. The evolution of knowledge on seafood spoilage microbiota from the 20th to the 21st century: Have we finished or just begun? *Trends in Food Science & Technology* 120: 236–46. [CrossRef]

Bai, Chunguang, Patrick Dallasega, Guido Orzes, and Joseph Sarkis. 2020. Industry 4.0 technologies assessment: A sustainability perspective. *International Journal of Production Economics* 229: 107776. [CrossRef]

Bellmann, Christophe, Alice Tipping, and U Rashid Sumaila. 2016. Global trade in fish and fishery products: An overview. *Marine Policy* 69: 181–88. [CrossRef]

Bertossi, Alberto. 2024. Pathways towards food sector sustainability:the case of vending. *Agricultural and Food Economics* 12: 13. [CrossRef]

Campos, Bente Castro, and Xue Qi. 2024. A literature review on the drivers and barriers of organic food consumption in China. *Agricultural anf Food Economics* 12: 18. [CrossRef]

Caswell, Julie A. 2006. Quality assurance, information tracking, and consumer labeling. *Marine Pollution Bulletin* 53: 650–56. [CrossRef]

Cheng, Qiao, Changqi Liu, Jing Zhao, Weiwei Li, Fengxian Guo, Jiawei Qin, and Yaosong Wang. 2023. Unlocking the potential of hyaluronic acid: Exploring its physicochemica properties, modification, and role in food applications. *Trends in Food Science & Technology* 142: 104218. [CrossRef]

Dao, Thi Bich Thuy, and Van Quy Khuc. 2023. The Impact of Openness on Human Capital: A Study of Countries by the Level of Development. *Economics* 11: 175. [CrossRef]

Echegaray, Noemí, Abdo Hassoun, Sandeep Jagtap, Michelle Tetteh-Caesar, Manoj Kumar, Igor Tomasevic, Gulden Goksen, and Jose Manuel Lorenzo. 2022. Meat 4.0: Principles and Applications of Industry 4.0 Technologies in the Meat Industry. *Applied Science* 12: 6986. [CrossRef]

Eguiraun, Harkaitz, Urtzi Izagirre, and Iciar Martinez. 2015. A paradigm shift in safe seafood production: From contaminant detection to fish monitoring-Application of Biological warning systems to aquaculture. *Trends in Food Science & Technology* 43: 104–13. [CrossRef]

FAO. 2020. *The State of World Fisheries and Aquaculture 2020*. Rome: Food and Agricultural Organization of the United Nations. [CrossRef]

FAO. 2022. *Thinking about the Future of Food Safety*. Rome: Food and Agriculture Organisation of the United Nations. [CrossRef]

Fleiß, Eva, Stefanie Hatzl, and Jürgen Rauscher. 2024. Smart energy technology: A survey of adoption by individuals and the enabling potential of the technologies. *Technology in Society* 76: 102409. [CrossRef]

Fox, Michaela, Mike Mitchel, Moira Dean, Christopher Elliott, and Katrina Campbell. 2018. The seafood supply chain from a fraudulent perspective. *Food Security* 10: 939–63. [CrossRef]

Gephart, Jessica A, and Michael L. Pace. 2015. Structure and evolution of the global seafood trade network. *Enviromental Research Letters* 10: 125014. [CrossRef]

Ghobakhloo, Morteza. 2020. Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production* 252: 119869. [CrossRef]

Grabowska, Sandra. 2018. Industry 4.0: The Future of Smart Factories. *International Journal for Research in Applied Science & Engineering Technology* 6: 1955–58.

Graham, Robin D., Ross M. Welch, David A. Saunders, I. Ortiz-Monasterio, Howarth E. Bouis, Merideth Bonierbale, S. de Haan, Gabriella Burgos, Gaa Thiele, Reyna Liria, and et al. 2007. Nutritious Subsistence Food Systems. *Advances in Agronomy* 92: 1–74. [CrossRef]

Ha, Thanh Mai, Gordana Manevska-Tasevska, Martin Weih, and Helena Hansson. 2024. Heterogeneity in farmers' stage of behavioural change in intercropping adoption: An application of the Transtheoretical Model. *Agricultural and Food Economics* 12: 12. [CrossRef]

Hassoun, Abdo, Shahida Anusha Siddiqui, Slim Smaoui, İlknur Ucak, Rai Naveed Arshad, Paula Garcia-Oliveira, Miguel A. Prieto, Abderrahmane Aït-Kaddour, Rosa Perestrelo, José S. Câmara, and et al. 2022. Seafood Processing, Preservation, and Analytical Techniques in the Age of Industry 4.0. *Applied Science* 12: 1703. [CrossRef]

Jamwal, Anbesh, Rajeev Agrawal, Monica Sharma, Vikas Kumar, and Sundeep Kumar. 2021. Developing A sustainability framework for Industry 4.0. *Procedia CIRP* 98: 430–35. Available online: https://www.researchgate.net/publication/349973096 (accessed on 13 November 2024). [CrossRef]

Jensen, Helen H. 2006. Changes in seafood consumer preference patterns and associated changes in risk exposure. *Marine Pollution Bulletin* 53: 591–98. [CrossRef] [PubMed]

Jiao, Xidong, Huayu Yang, Xingying Li, Hongwei Cao, Nana Zhang, Bowen Yan, Bo Hu, Jianlian Huang, Jianxin Zhao, Hao Zhang, and et al. 2024. Green and sustainable microwave processing of surimi seafood: A review of protein component interactions, mechanisms, and industrial applications. *Trends in Food Science & Technology* 143: 104266. [CrossRef]

Johansen, Ulf, Heidi Bull-Berg, Lars H. Vik, Arne Stokka, Roger Richardsen, and Ulf Winther. 2019. The Norwegian seafood industry—Importance for the national economy. *Marine Policy* 110: 103561. [CrossRef]

Kasza, Gyula, Judit Oláh, József Popp, Zoltán Lakner, László Fekete, Enikő Pósa, Widya Satya Nugraha, and Dávid Szakos. 2024. Food miles on the shelves: The share of local food products in the Hungarian retail sector. *Agricultural and Food Economics* 12: 3. [CrossRef]

Kathuria, Deepika, Anju K. Dhiman, and Surekha Attri. 2022. Sous vide, a culinary technique for improving quality of food products: A review. *Trends in Food Science & Technology* 119: 57–68. [CrossRef]

Kaushal, Sushant, Dushyanth Kumar Tammineni, Priya Rana, Minaxi Sharma, Kandi Sridhar, and Ho-Hsien Chen. 2024. Computer vision and deep learning-based approaches for detection of food nutrients/nutrition: New insights and advances. *Trends in Food Science & Technology* 146: 104408. [CrossRef]

Kurian, Simmy, Hareesh N Ramanathan, and Barbara Pisker. 2022. The Correspondence of Culture and E-Learning Perception Among Indian and Croatian Students During the COVID-19 Pandemic. *Asia Pacific Journal of Information Systems* 32: 656–83. [CrossRef]

Lin, Jun, Zhiqi Shen, Anting Zhang, and Yueting Chai. 2018. Blockchain and IoT based Food Traceability for Smart Agriculture. Paper presented at ICCSE'18: Proceedings of the 3rd International Conference on Crowd Science and Engineering, Singapore, July 28–31; pp. 1–6. [CrossRef]

Majumder, Ranendra K., and Amjad K. Balange. 2023. *Advances in Fish Processing Technologies: Preservation, Waste Utilization, and Safety Assurance*. New York: Apple Academic Press Inc. [CrossRef]

Mamine, Fateh, and M'hand Farès. 2020. Barriers and Levers to Developing Wheat–Pea Intercropping in Europe: A Review. *Sustainability* 12: 6962. [CrossRef]

Manful, Maame Ekua, Lubna Ahmed, and Catherine Barry-Ryan. 2023. New Approach Methodologies (NAMs) for safety testing of complex food matrices: A review of status, considerations, and regulatory adoption. *Trends in Food Science & Technology* 142: 104191. [CrossRef]

Martini, Martini, Doddy Setiawan, Retno Tanding Suryandari, Rayenda Khresna Brahmana, and Andi Asrihapsari. 2023. Determinants of Digital Innovation in Micro and Small Industries. *Economies* 11: 172. [CrossRef]

Papakostas, Nikolaos, Carmen Constantinescu, and Dimitris Mourtzis. 2020. Novel Industry 4.0 Technologies and Applications. *Applied Sciecnes* 10: 6498. [CrossRef]

Peng, Daomin, Qian Yang, Hyun-Joo Yang, Honghong Liu, Yugui Zhu, and Yongtong Mu. 2020. Analysis on the relationship between fisheries economic growth and marine environmental pollution in China's coastal regions. *Science of The Total Environment* 713: 136641. [CrossRef]

Rahman, Airini Ab, Umar Zakir Abdul Hamid, and Thoo Ai Chin. 2017. Emerging technologies with disruptive effects: A review. *PerintiseJournal* 7: 118–28.

Rane, Shivam, and Pritesh Shah. 2022. Survey of Technologies for Industry 4.0. Paper presented at 2022 6th International Conference On Computing, Communication, Control And Automation (ICCUBEA), Pune, India, August 26–27; August 26. [CrossRef]

Rönnbäck, Patrik. 1999. The ecological basis for economic value of seafood production supported by mangrove ecosystems. *Ecological Economics* 29: 235–52. [CrossRef]

Russo, Giovanni Luca, Antonio L. Langellott, Elena Torrieri, and Paolo Masi. 2023. Emerging technologies in seafood processing: An overviewof innovations reshaping the aquatic food industry. *Wiley: Analytical Science* 23: e13281. [CrossRef]

Tran, Aí Huu. 2020. Competitiveness of seafood enterprises: The case study of Ba-Ria-Vung-Tau province, Vietnam. *Web of Conferences* 164: 06001. [CrossRef]

Virdin, John, Tibor Vegh, Blake Ratcliff, Elizabeth Havice, Jack Daly, and Jack Stuart. 2022. Combatting illegal fishing through transparency initiatives: Lessons learned from comparative analysis of transparency initiatives in seafood, apparel, extractive, and timber supply chains. *Marine Policy* 138: 104984. [CrossRef]

Yasuda, Tomohide, and Robert E. Bowen. 2006. Chain of custody as an organizing framework in seafood risk reduction. *Marine Pollution Bulletin* 53: 640–49. Available online: www.elsevier.com/locate/marpolbul (accessed on 13 November 2024). [CrossRef]