Discover Food

Review

From catch to consumer: enhancing seafood processing management with Industry 4.0 innovations

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Abstract
The incorporation of Industry 4.0 technologies into the seafood processing sector presents a transformative potential for improving efficiency, sustainability, and transparency throughout the supply chain. This study aims to examine the impact of such technological advancements, including automation, robotics, blockchain, computer vision, AI, and IoT, on the seafood industry's operations, ranging from sorting, cleaning, and packing to quality assessment and product preservation. Conducted through a Systematic Literature Review (SLR) of Web of Science-indexed papers, this research assesses the synergy between innovation and business 4.0 technologies in seafood processing. Our findings suggest that these technologies not only promise enhanced operational efficiency and product quality but also offer sustainable practices through energy-efficient methods, waste management techniques, and innovative packaging solutions. Additionally, the study addresses the workforce implications, underscoring the shift in job roles towards more specialized and value-added positions rather than outright displacement. The primary data collected and analyzed herein underscores the critical role of Industry 4.0 in promoting sustainable resource management, optimizing processes, and ensuring ecological responsibility within the seafood sector, thereby contributing to the broader goals of food security and environmental sustainability.

1 Introduction

The food business has grown and undergone revolutions around the supply chain including food manufacturing technologies, methods, and customer needs. Human nutrition technology has improved significantly, from harvesting to stem cell technology, and 3D printing, which are slowly getting accepted in the industries. With the high demand and needs of customers like ready to eat ready to cook products, value-addition is also coming to its peak in many countries [1, 2]. Artificial intelligence (AI), smart sensors machine learning (ML), robotics, and extensive data analysis are among the critical technologies used in the industry 4.0 (4th Industrial Revolution) [2], microwaves, ultrasound sensitive computerized sensors high pressure-based technologies, biotechnology, spectroscopy, spectrometry nanotechnology, chromatography, [2], and other technical innovations are being developed and applied in the food industry [3]. In a Systematic Literature Review, this article explores the significance of technical advancements in the seafood sector in relation to industry 4.0.

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A systematic literature review (SLR) finds, selects, and critically evaluates material on a certain topic. Before beginning the investigation, the systematic review should follow an established approach or plan with well-defined criteria. It requires creating a well-considered search approach with a specific focus or resolving a specific problem. The overview explains the information obtained, assessed, and reported within the parameters stated. The evaluation must strictly contain search keywords, tactics (database names, platforms, and search dates), and strict restrictions [4].

A bibliometric analysis was also carried out using "VOSviewer Application", emphasizing various elements of the advancement of scientific literature and finding 10 clusters, notably theories, technologies, techniques, nations, and research themes: "Seafood," "Industry 4.0," "Technology," and "Sustainability." [5], and current and future implications, from which the discussion on Industry 4.0 was more required [6]. The after-effects of the coronavirus pandemic scenario have also aided in the rapid development and acceleration of Industry 4.0, and the acceptance of its technologies was discussed by [7]. This paper undertakes a tier-one analysis of worldwide food and beverage publications, identifying trends and changes [8].

Seafood being highly perishable and spoils quickly, the fourth industrial revolution has a crucial element in addressing numerous emergent difficulties. These technologies have the potential to address all the problems while also extending the shelf life of fish and other seafood, according to studies from numerous research articles that are provided in this publication. Hassoun et al. [2] addressed this issue emphasized the need for thorough research and understanding on the subject.

The following questions are listed and explored in the study. What are the present technology adaptations in seafood processing industry? How will technological innovation under Industry 4.0 affect the future of the seafood industry? Will the seafood sector accept the industrial revolution under the 4th generation? How will the technology introduced into the processing industry replace the skilled workers in the seafood processing sector? How can Industry 4.0 application in the seafood industry lead to a sustainable resources management effect?

2 Materials and methods

The Systematic Literature Review approach is used in this study to assess the areas under consideration. According to the theoretical framework offered, an exact SLR generally assists in generating a solid understanding of what is known in a subject field, detecting research trends and trajectories, and setting a research plan [9]. "The growth of evidence-based practice has resulted in an increasing variety of review types" [10].

A pool of academic contributions was obtained by conducting a keyword search of Web of Science-indexed papers. Web of Science was chosen as the database because it offers complete scientific, technological, and sociological content from all relevant scientific publications [6]. Finally, the search implication was restricted to a single covering period, which included all industry 4.0 research until 2023. Progressively a deeper understanding of the growth of the interaction between innovation and business 4.0 technologies in seafood processing companies is gained. The study followed a definite path in the systematic literature. The initial stage was the identification of the study questions, followed using the SLR technique. Then the identified papers were analyzed on different parameters using the software and then the analysis and discussion were done.

3 Result and discussion

3.1 Analysis using VOSviewer

A bibliometric analysis was also carried out, emphasizing various elements of the advancement of scientific literature and finding 10 clusters, notably theories, technologies, techniques, nations, and research themes: "Seafood," "Industry 4.0," "Technology," and "Sustainability."

Although VOSviewer is primarily meant for bibliometric network analysis, it may also be used to construct, visualize, and explore maps based on network data. The clusters shown in Table 1 depicts the relationship between author keywords obtained by Fig. 2, where the interaction between 4 major categories have been mentioned and they are: Seafood, Technology, Sustainability and Safety and Quality.

Figure 1 depicts approaches for investigating technical innovation in the context of the 4.0 paradigm for the seafood processing sector. However, there is a disparity in the cited theories and conceptual frameworks employed to analyze the topic. [6]. Each cluster illustrates a topic-based explanation that directly and indirectly connects the paper keywords Fig. 1. The figure shows 200+ keywords divided into four groups with four color variations. The primary connecting

Table 1 Clusters and Keywords

Sl. No	Clusters	Mapped colour	Keywords
1	Cluster-1	Green	Seafood, Fish Food Safety, Meat Proteins, Processing etc
2	Cluster-2	Red	Sustainability, Sustainable development, Industry 4.0, Supply chain management, Quality control, Food industries, Developing countries, etc
3	Cluster-3	Yellow	Human, Aquaculture, Food Processing, technology
4	Cluster-4	Blue	Non-Human, Metabolism, Chitosan, Chemistry, Food control, Isolation and purification

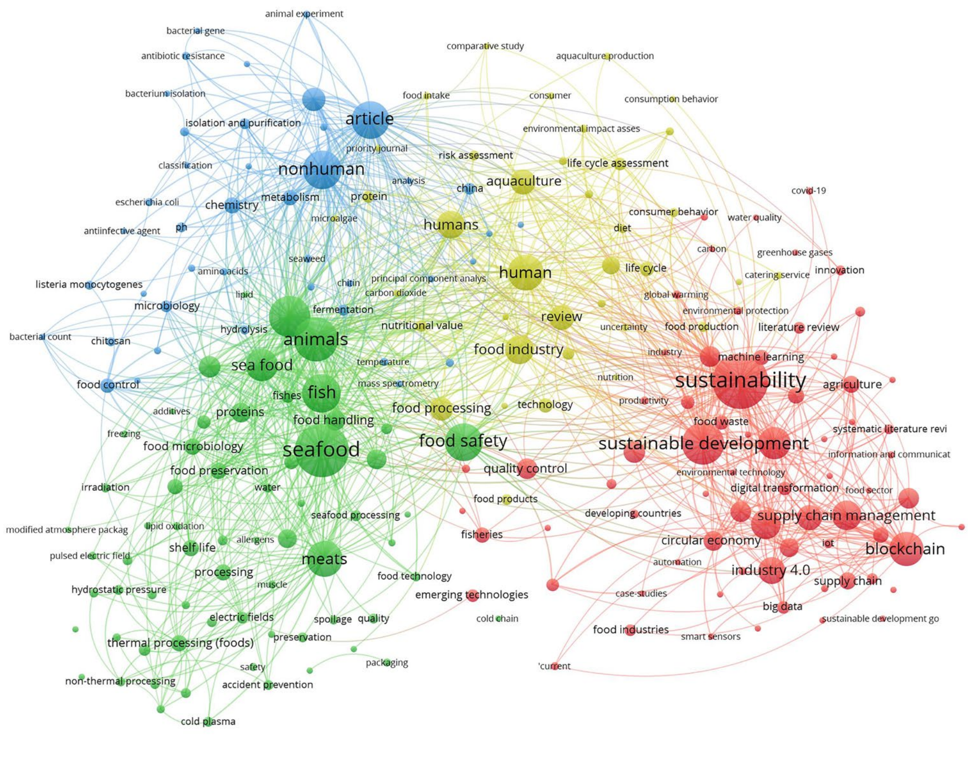

Fig. 1 Network based on Co-occurrence Keyword Map. Source: Map created through the VOSviewer application

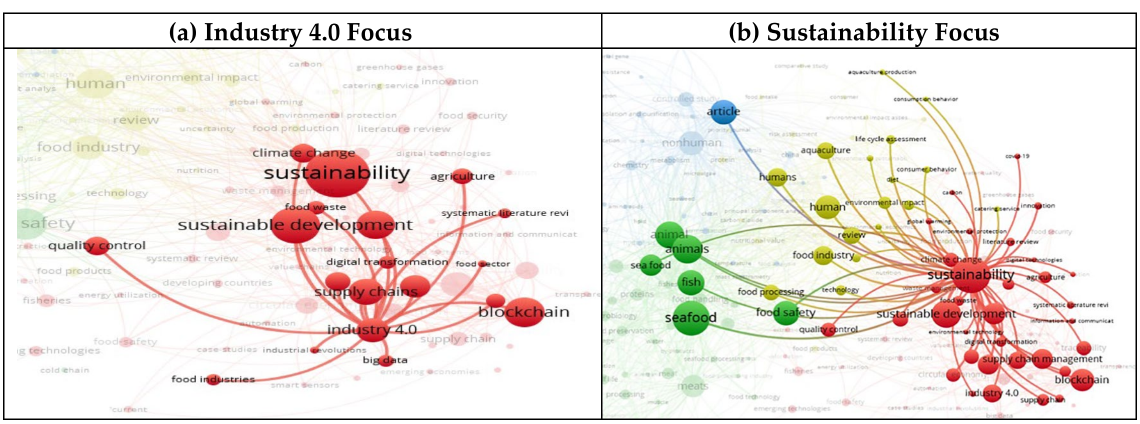

Fig. 2 Highlights sustainability and Industry 4.0 from Network based on Co-occurrence Keyword Map. **a** Industry 4.0 Focus. **b** Sustainability Focus. Source: Map created through the VOSviewer application

words are "SEAFOOD," "FOOD SAFETY," "SUSTAINABILITY," "NON-HUMAN," "FOOD INDUSTRY," "SUSTAINABLE DEVELOPMENT," "BLOCKCHAIN," and "INDUSTRY 4.0".

The figure was emphasized and used to investigate the significance of sustainability in the framework of business 4.0 in the seafood processing business (Fig. 2).

Figure 3a displays the interaction and linkages between the 10 clusters constructed using input data from the Web of Science. On the map, the author's name and the year of publication have been filtered.

The clusters in Table 2 correspond to the major and minor conceptual frameworks employed in each research papers, which were chosen and divided based on keyword variation. The topic chosen for review here is seafood industry in line with Industry 4.0, the papers obtained include different clusters, and an outcome of 10 groups was obtained from the VOSviewer application.

The inverse of co-citation is bibliographic coupling. If both publications cite a third publication, the two publications are bibliographically connected. Bibliographic coupling refers to the overlap in published reference lists illustrated in Fig. 4. This bibliographic coupling is based on the same database configuring the other maps. These maps were used to address the research questions thus formed and are explained under.

3.1.1 What are the present technology adaptations in seafood processing industry?

Seafood is an essential component of a completely healthy diet. The technology discussed in this research paper has been shown because of its high protein content, it has been demonstrated to include micronutrients like vitamins and minerals. It also contains a high concentration of LC-PUFAs (or Omega-3), namely eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [11]. Seafood, on the other hand, is very perishable and rapidly degrades. Innovative technology like ultrasonic, irradiation, high-pressure manufacturing, cold pulsed electric field, plasma, radiofrequency, and pulsed frequency are being used to overcome these challenges with the advent of Industry 4.0 [12]. These forms of technology can overcome the barriers and extend the life of fish for food [2]. Formaintaining fish quality and sustainable fishing methods, sophisticated processing and post-harvest technologies are required. Hence the sophistication technology has brought up great importance due to the requirement of the customers.

Wild-caught fish is first washed and cleaned onboard the fishing vessel and then sorted according to size and species before being shifted to the fish hold for storage [13]. Farm-raised fish should be stunned first, as soon as it is harvested, and then bled in specific tanks with running water facilities built for the purpose before being further processed. This will reduce postmortem alterations and retain nutritional content. Bleeding is carried out in specialized tanks with fresh seawater circulation. Processing starts from de-heading, scaling, filleting, forming and freezing, the process stages and style vary according to the customer requirements. The seafood processing sector could achieve several innovations through automation and ICT applications, which enabled the industry to uphold high quality standards and get rid of

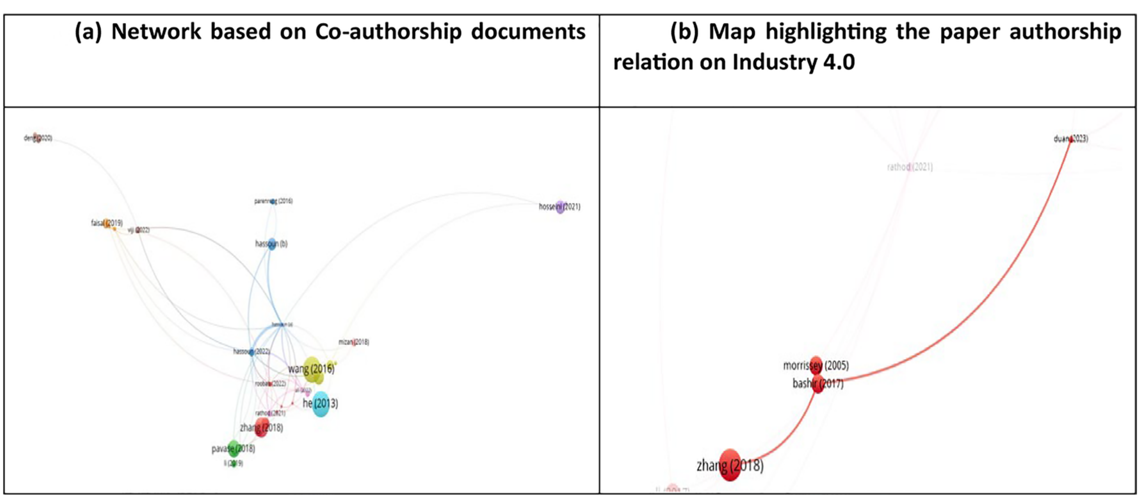

Fig. 3 Interaction and linkages between the 10 clusters. **a** Network based on Co-authorship documents Map. **b** Map highlighting the paper authorship relation on Industry. Source: Map created through the VOSviewer application

Table 2 Clusters and authors

Sl. No	Paper Author	Sl. No	Paper Author
Cluster I		4	Wang (2018)
1	Bashir (2017)	**Cluster VI**	
2	Duan (2023)	1	Cho (2021)
3	Li (2017)	2	He (2023)
4	Morrissey (2005)	3	Huang (2023)
5	Roobab (2022)	4	Negrara (2021)
6	Sun (2023)	**Cluster VII**	
7	Zhang (2022a)	1	Dong (2022)
Cluster II		2	Faisal (2019)
1	Chelliah (2021)	3	Faisal (2020)
2	Kuuliala (2019)	**Cluster VIII**	
3	Li (2019)	1	Deng (2020)
4	Pavase (2018)	2	Deng (2021)
5	Sagar (2022)	3	Viji (2022)
6	Tong (2021)	**Cluster IX**	
7	Zhang (2022)	1	Ali (2022)
Cluster III		2	Elumalai (2019)
1	Hassoun (2022)	3	Rathod (2021)
2	Hassoun (a)*	**Cluster X**	
3	Hassoun (b)**	1	Ashrafudoulla (2023)
4	Parenreng (2016)	2	Mizan (2018)
5	Tsolakis		
Cluster IV			
1	Ali (2021)		
2	Nazir (2019)		
3	Rubino (2023)		
4	Wang (2016)		
Cluster V			
1	Chen (2022)		
2	Hosseini (2021)		
3	Tan (2022)		

Source: Output from VOSviewer application

(a) & (b) **this shows the sub papers under the same author in the same year

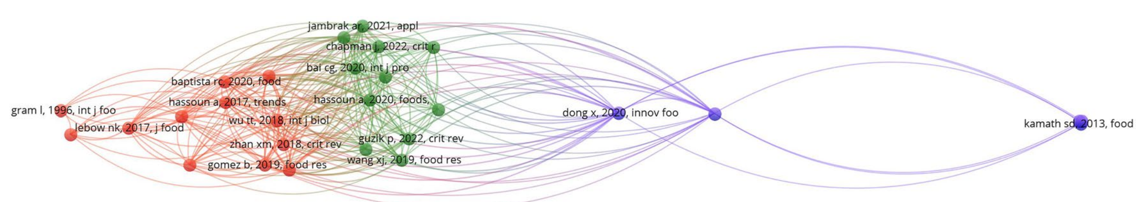

Fig. 4 Bibliographic-Coupling Map. Source: Map created through the VOSviewer application

production line defects in processing of various seafood items like fillets, where unit get reduced thereby increasing the value and shelf life of catch.

The ability to objectively assess the fillet quality is necessary for a machine to automatically identify and eliminate quality flaws. With the application of cameras, sensors, and lighting technologies to simulate human vision, computer vision has advanced significantly in recent years [14]. As Einarsdóttir et al. (2022) highlighted that AI and vision technologies have also been utilized in shellfish processing to identify bits of shell following shrimp peeling.

Papers that link with the article are from Fig. 3a. Zhang et al. [15] on Chaof ranges in chemical gel from silver carp fillets while processing it through setting and heating. The influence of increased gel strength on the effects of different washing solutions is demonstrated by the calcium chloride 0–2% washing solution [16]. This work examines knowledge transfer to small and medium-sized (SMEs) using a dynamic research model that can improve future seafood processing technology preservation. The remaining papers in the first cluster discuss new technology for preserving muscle and meat quality through high-pressure processing and extending the product's shelf life.

The second cluster from Fig. 3a (reference to Table 2) includes seven major papers [17] illustrating on innovative and interactive packaging and IMedBox, the authors' universal and preventative medication management system. Controlled delamination (CDM) seals and regulated wireless technology were also studied in new medication packaging [17]. Li et al. [18] evaluated that presently there are various types of packaging. Smart, interactive, active, ergonomic, and intelligent packaging advances all have an influence on passive packaging. Intelligent packaging is a fully integrated system with intelligent features such as detecting, sensing, recording, tracing, and communicating. The primary goals are to increase shelf life, improve safety and quality, gives information, and send alerts on possible concerns and thereby assuring environment sustainable material. As a result, wireless connectivity through biological sensors could categorize critical characteristics. High-performance design enables immediate care and prediction of these crucial aspects. The employment of statistics and modelling in tandem improved the efficacy of the quality characterization process [19, 20] as well as the pragmatic application resulting the food quality monitoring. To confirm the quality of food, key public issue, and dependable sensors or systems for monitoring are required [21].

Zaragozás et al. [20] in his paper, refers to the simultaneous use of statistics and modeling as extremely helpful for the quality characterization process. To confirm the quality of diverse food commodities, a document addressing the safety and quality of food, a key public issue, and dependable sensors or systems for monitoring are required [22]. Chemosensors are a novel sensing device being researched and developed in the food sector, with immense potential for enabling onsite monitoring of food quality and safety. One strategy to assist SMEs in developing and increasing their competitiveness in the global market is through technology transfer. The new approaches are needed with the adoption of revolutionary technologies and getting around persistent barriers between researchers and industry [16].

It can be concluded that, technology improvements have been significantly reflected in the biochemical processes that have been in use in the seafood industry from the traditional time. New mythological launches obtained greater result acceptability, demonstrating the need of comprehensive modification of machinery and other accessories in the business. The requirement for better waste management practices in the company premises with better technology interaction is also a case to be discussed. With the introduction of Industry 4.0, advanced technologies mentioned above would be ultimately applied to the seafood processing sector.

3.1.2 How will technological innovation under Industry 4.0 affect the future of the Seafood Industry?

When the seafood sector is considered, it enormously contributes to the world economy, accounting for about 8% of the global demand for protein [23]. With increasing customer demands, emerging techniques are being studied to supplement preservation procedures to ensure non-hazardous food and increase shelf life without compromising food safety with quality. In this way, modern cold-based storage techniques like chilling and super chilling contrast traditional storage methods like freezing and refrigeration are being adopting the latest materials for construction and endorsement in the technological sides Zhang et al. [15] suggested two advanced systems of compression aided ammonia water absorption refrigeration circuits that use the ocean's energy to satisfy seafood freezing and storage refrigeration requirements in coastal and offshore island areas. Cascade refrigeration systems (CRS) have been identified as promising to increase energy efficiency while fulfilling multiple temperature targets [24]. Investigations were also made to assess the in-fluence of alternating pressure on energy efficiency and primary energy rate ratio in refrigeration systems. The use of innovative food packaging techniques (edible films and coatings) and differential scanning calorimetry (DSC) studies of glass transition temperatures for mixed zein films over the water content range revealed that sunflower oil has a plasticity influence on the film [25, 26], as well as a new method of storing food called storage under extreme conditions, which uses storage pressure control to thwart microbial growth and subzero refrigeration and room temperatures both postpone organoleptic deterioration [27, 28].

The development of intelligent packaging [29, 30] was classified and mapped using circular economy principles, including the primary motivations and hurdles that might aid or impede the increase in packing with increased traits and potential benefits businesses can obtain. While a model for sophisticated monitoring of freshness with continuous surveillance food freshness is preserved as a barrier for both food producers and end users due to the lack of portable detection devices, affordable, and efficient have yet to be commercialized, have developed a simple sensor system based on a cell phone app that includes a real-time deeper learning model freshness of food monitoring (see Fig. 3a), [31]. The utilization of cellulose paper for colorimetric indicator bars was introduced through a novel approach involving UV-induced crosslinking of synthesized Gelatine methacryloyl (GleMA) along with encapsulated bromocresol green (BCG).

The third cluster shown in Fig. 2b directly deals with Industry 4.0, as illustrated in papers [32, 33]. The phrase "Industry 4.0" was coined by a German federal government project, including academics and commercial businesses, in 2011. This project was related to a strategy program to build the most sophisticated production methods to enhance domestic industry productivity and efficiency in Germany [34]. The study presented here provides an understanding of Industry 4.0 by text mining of associated materials [35]. The journal papers, 660 in number, were identified as those having the keywords "Industry 4.0" or "fourth industrial revolution" from the Web of Science Core Collections, containing all available data published was taken from [36].

The seafood industry is working on improved food safety and shelf-life strategies. Cold storage technologies, environmentally friendly, [13] creative food packaging, and the creation of smart packaging are all being researched. Using smartphone app sensor technologies, continuous food freshness tracking is being created. Hence a major focus is Industry 4.0 in future.

3.1.3 Will the seafood sector accept the industrial revolution under the 4th generation?

Industry 4.0 has received much attention in the recent literature. However, there is a dearth of systematic and comprehensive research reviews that reflect the topic's dynamic nature [37, 38]. Figures 1 and 2b establishes the connection between industry 4.0 and its importance in the current situations through the latest publication, with the present twentieth century proving its state and importance. Various cutting-edge technologies are included in Industry 4.0, including ERP, sensory monitoring systems [39], and modernized artificial intelligence technology for improved quality control systems. AI accommodates innovation analytics [40], the fundamental process of generating insights, models, and visualizations through computer-based data analysis, coupled with creative problem-solving, fosters innovation and facilitates progress [41]. Digital, biological, and physical worlds and new technologies distinguish Industry 4.0 [42].Incorporating Artificial Intelligence (AI) and blockchain technology (BCT) into supply chains offers substantial benefits, including improved operational capabilities, support for sustainable growth, data monetization, and leveraging cutting-edge technologies like cloud computing, robotics, 3D printing, advanced wireless technologies, and the Internet of Things (IoT) [43].

Furthermore, upcoming technologies such as fifth generation (5G) communications, which include the Internet of Things (IoT) [44], blockchain, artificial intelligence, and so on, will hasten global business change. 5G technology is intended to unlock gigantic IoT ecosystems by enabling immense connections for many IoT devices with excellent data rates, ultra-low latency, and low-cost access. The 5G networks will provide the performance required for massive IoT and allow a perceived ultimately linked world. Meanwhile, blockchain is being pushed as the foundation for a new business model in future IoT (IoT) [45]. This Fig. 2b is generated using a group of keywords with reference to Table 1, generally expressed from Industry 4.0 that emphasizes the significant linkages of other keywords that directly relate to the relevance of Industry 4.0. It is directly associated with seafood processing, where cutting-edge technologies like ohmic heating, pulsed electric field high-pressure processing, and nanotechnology are well discussed in these papers [46, 47], advanced mass spectrometry, Smart labels are mentioned in [48], Others were discussed and mentioned [49]. Electronic noses that replicate the human nose have been created to detect food quality and infection. The e-nose gadget appeared to be easier to use, more effective, and less expensive; it was an effective tool for environmental monitoring, proposed by Choudhari et al. [47].

Clusters four, five, six, and seven from Figs. 1, 2b and 3a discuss other emerging technologies in processing sectors based on nutritional values of food and quality maintenance, like the green technique for valuing chestnut shells developed [21]. Another experiment that came to be effective and like the devised approach was used to determine trace Bisphenols in canned meat, with recoveries ranging from 73 to 117%, indicating a possible use for pretreatment in complicated materials [50]. This research paper demonstrates the utilization of nonthermal processing techniques, such as pulsed electric field (PEF), dense phase carbon dioxide (DPCD), high hydrostatic pressure (HHP), membrane technology, ultrasound-assisted extraction (UAE), and enzyme-assisted extraction, to extract bioactive compounds from marine byproducts [51]. Another idea put forward by [52] is the presence of polyunsaturated fatty acids and carotenoids in prawn oil makes it healthier than other fish oils. The technique of extracting SPBP oil can be improved by lowering the requirement for solvents and increasing yield. By modifying the procedures, drawbacks can be managed. A product with added value for the sustainability of the prawn industry and marine resources can be a stable form produced employing techniques at the industrial level. Comparing non-thermal technologies to conventional techniques, they produced more favorable results in terms of output, quality, energy, and time costs for extracting bioactive chemicals from marine by-products. This shows that implementing non-thermal alternatives could potentially improve food security while reducing environmental issues [53].

A review of the latest knowledge about hydrophobic marine-derived bioactive compounds' nanostructured delivery vehicles and methods of the production highlighted their potential use in functional food since they enhance their organoleptic properties and lower their toxicity was mentioned by Hosseini et al. [54]. In commercial and research applications, HPP technology is utilized to combine pressure with bio-preservation to achieve certain product features. This study also discusses new results in microbiology, chemistry, and molecular biology [55]. Astaxanthin, a xanthophyll carotenoid pigment found in shellfish, crabs, and seaweeds, can be utilized as an ingredient in food products to maintain freshness, color, flavor, quality, and other factors. According to current research on the combination of astaxanthin and nanotechnology, the encapsulation of astaxanthin in nanocarriers improves the solubility, stability and permits a wide range of applications due to its enhanced bioavailability in digestive, endocrine, and nervous systems [56]. Texture modified foods are becoming more and more popular among the elderly since they are easier for old and dysphagic individuals to chew. A study on application of herbal extract to improve the consistency of texture of yellowfin sole (Pleuronectes aspera), prior to grilling with superheated steam, revealed that marinating fish with herbal extracts results in soft texture, improved sensory quality, and ease of ingest for elderly people [57]. Figure 1 describes the paper connection and its correlation through Co-Citation mapping on the above-mapped clusters. Each paper shows a link to the technological aspects of the seafood industry, thereby stating the importance of technology and its adoption. It demonstrates the relationship between the citations and the associated paper conjunction, which is then visually shown.

Nevertheless, the progress in technology has significantly influenced various food matrices, showcasing advantageous improvements in terms of their physicochemical attributes, sensory characteristics, nutritional composition, and extension of shelf life [58]. The study focuses on current developments in biosensing techniques fand their application in food safety to establish relationship between small molecule pollutants in water and biological samples acquired from aquaculture and fisheries, such as heavy metals, antibiotics, biotoxins, and different seafood degradation factors. Also, it seeks the importance of advances in the biorecognition process, signal transduction approaches, and the quick advancement of element integration in each unique strategy, emphasizing the critical roles of revolutionary material science, simple platform manufacture, and intelligent readout [59].

Through comprehensive investigations into the functionalities, applications, and production techniques of FPCP protein hydrolysates, significant research patterns and future directions have emerged to capitalize on the economic and environmental benefits for the fish processing industry. FPCP hydrolysates have been found to possess desirable physical and chemical properties, such as emulsifying, foaming, and oil and water binding capacities. Additionally, they exhibit a diverse range of intriguing bioactivities, including anti-oxidative, anti-hypertensive, anti-microbial, and anti-anemia effects, which make them applicable in various food, nutritional, and pharmaceutical products. While chemical hydrolysis remains the most used method for producing crude FPCP protein hydrolysates, its limited control over product quality necessitates exploration of more precise alternatives [60].

Clusters eight, nine from Fig. 3a and b, and ten discuss food quality issues like the contamination of dried seafood during processing as well as handling in the storage can be affected by mycotoxins which are naturally poisonous secondary metabolites generated by molds or filamentous fungal species, the most dangerous of which include aflatoxins, ochratoxin A, deoxynivalenol, T-2 toxin, zearalenone, and fumonisins. Recent trends show an increase in the reports of mycotoxin contamination in dried fish products. To increase food safety, mycotoxins in dried fish items sold in markets must be monitored [61]. The other papers already show the interconnection with the previously mentioned cluster groups.

As a result of technological advancements, the adoption of new high-tech robotic equipment has already influenced the food business. As quality and safety go hand in hand with technology, this creates a route for other sectors, such as seafood, to expand and meet customer needs. Once the system becomes trendy, it will steadily spread for better marketing and product demand. Hence leading to the adaptation of the industry to 4.0, 5.0, and so on with time.

3.1.4 How will the technology introduce into the processing industry replace the skilled workers in the Seafood processing sector?

Professional employees are required for filleting, trimming, peeling, visual inspection, and quality control throughout the seafood processing process, from raw materials to consumable goods. According to an examination of Figs. 1 and 2b, the fish industry frequently requires assistance in hiring workers for processing plants. Jobs are often tedious, repetitious, and even hazardous. Seafood quality degrades fast, significantly, when temperatures rise. As a result, the product is constantly maintained cool and, the working environment is cold and wet, making it difficult for employees to stay for the entire shift [13].

Historically, the fish business has been labor-intensive, needing specialized workers to turn entire fish into consumable items. Because of the biological variety found in food items, automation in food production has been slower than in specific industries such as automobiles.

Since machines will never obtain the finishing provided by a skilled worker in their product, skilled labor has always been the fundamental foundation of prawns and other qualified processing requirements. Recent advancements in automated inspection, artificial intelligence, and robots are reshaping the food manufacturing business, providing new automation capabilities that have the potential to boost throughput and output. In the processing of crustaceans and shellfishes, AI and vision technology have also been utilized to detect shell fragments after prawns and mussels have been peeled says [13]. The changes brought up in the seafood industry and its transformation in the future is related in Fig. 3b.

Gripper technology is the design of tooling that can manipulate food products, such as picking products from a conveyor and placing in a tray. Gripping technology today often tries to resemble elements from nature, such as suction cups on octopuses' arms or grasping capabilities of human hands. Other advances that are on the horizon are mobile robots [62]; (Rubio et al., 2019) and collaborative robots, capable of performing in the harsh food production environment.

Due to the unsanitary practices of trained personnel, completed items may pose a disease threat to customers, causing trust and quality concerns for the company. The integration of AI and automation in industries can lead to both economic and social sustainability. While automation can improve efficiency and reduce costs, it can also lead to job displacement, causing unemployment and income inequality. Additionally, workers may need to acquire new skills or retrain to stay relevant, necessitating access to training and education opportunities. Therefore, balancing economic stability and social sustainability is crucial for ensuring the long-term success of the industry. As a result, appropriate resource management, monitoring systems, robotic interactions, and machine learning among expert employees can endure changing people's wants.

3.1.5 How can Industry 4.0 application in the seafood industry lead to a sustainable resources management effect?

Figure 2 and Table 1 illustrates the author key words correlating about 200+ papers related to sustainability, sustainable development, seafood, fish, food safety, food industry, and Industry 4.0 and supply chain management.

Based on recent studies, the advancements in industry 4.0 technologies have the potential to enhance food sustainability, leading to more environmentally friendly food production and consumption practices. Intelligent applications in the food manufacturing sector (smart factories) and agricultural production systems (brilliant/precision agriculture and farming) hold the promise to accelerate the adoption and integration of Industry 4.0 technology [32]. This indeed creates easy access of seafood sources to the demand for ready-to-eat, ready-to-cook products. Numerous recent publications have highlighted the pivotal significance of Industry 4.0 technologies in reducing and upcycling food waste, enhancing food quality, enabling better food traceability, and fostering the creation of healthier and ecologically sustainable food products. The emerging notion of "Food Quality 4.0" entails leveraging Industry 4.0 technologies in food analysis to achieve rapid, reliable, and unbiased evaluations of food quality. This concept was thoroughly explored and discussed in the mentioned source [63]. The figure depicts the fundamental technologies of Industry 4.0 utilized to develop intelligent food factories and farms, enhance food quality, safety, and traceability, reduce food waste and energy consumption, as well as create novel and healthier food options [5].

The research encompassed peer-reviewed publications, grey literature, relevant networking websites, and conference proceedings focusing on the application of eco-friendly technology and Industry 4.0 enablers in promoting food sustainability. The primary aim was to underscore the significance of these cutting-edge solutions as essential elements of increasingly sustainable agricultural system [5]. Hence technological advancements with a parallel focus on sustainability can meet demand by future generations for seafood resources.

4 Conclusion

The seafood sector is predicted to benefit from sector 4.0, which includes automation and robots to improve operations like sorting, cleaning, and packing, decreasing labor costs and increasing productivity. Blockchain technology is being investigated for transparency, while sophisticated technologies like computer vision and AI are being utilized to evaluate the quality of marine items. Energy-efficient technology and waste management techniques are among the sustainable practices that are being used. The shelf life of products is being extended by using innovative packaging techniques including modified environment and vacuum packing. While cutting-edge processing methods are being developed, IoT devices are being utilized to monitor and regulate parameters. Hygiene precautions are being improved, and energy efficiency is being optimized. Direct sales to consumers and online marketplaces are also used.

Overall, the implementation of industry 4.0 technologies in the seafood sector has the potential to increase efficiency, quality, sustainability, and transparency across the supply chain. It is crucial to emphasize, however, that these developments are not without hurdles, such as the need for early investment, labor adaptability, and cybersecurity issues. The integration of digital, green, and innovation strategies for sustainable economic development is also a key factor for future revolutionary change [64]. Compared to the Industrial Revolution, other sectors, such as communications systems, textile systems, and so on, have secured the fifth revolutionary voyage.

The advent of technology in the seafood processing business can have an influence on the jobs of experienced personnel, although it does not necessarily completely replace them. Instead, it frequently changes their jobs, forcing people to adapt to new methods of functioning. Automation of repetitive jobs, shift towards technical competence, quality control, maintenance, data management, training, innovation, process improvement, cooperation with technology, complicated problem-solving, and regulatory compliance are all examples of this. Instead of displacing talented individuals, technology changes their positions within the sector to more specialized and value-added jobs.

Hassoun et al. [65] presents an overview of Industry 4.0 technologies in the food processing industry, focusing on robotics, smart sensors, artificial intelligence, the Internet of Things, and Big Data as key enablers. These technologies include quality control, safety, and production efficiency. They emphasize the need for detailed studies to address challenges and provide insights into each enabler. This indeed also highlights the need for workers to acquire new skills or retrain to stay relevant in the workforce, emphasizing the importance of access to training and education opportunities.

Industry 4.0 technologies have the potential to greatly enhance sustainable resource management in the seafood sector. These technologies can enable ecologically responsible and sustainable marine resource management by optimizing procedures, minimizing waste, and improving traceability. Benefits include effective resource utilization, decreased waste and byproducts, sustainable fishing practices, traceability and transparency, ecosystem monitoring, energy efficiency, predictive analytics, closed-loop systems, cooperation, knowledge sharing, and compliance monitoring. These developments lead to a more sustainable approach to seafood production, which benefits both the industry and the environment.

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Declarations

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