Human Cost for Ship Recycling: A Review of Current Occupational Safety and Health Practices in Major Recycling Facilities

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Abstract: Research studies on ships and shipbuilding have garnered significant interest worldwide. However, there is a shortage of scientific literature about ship recycling, shipbreaking, and safe-end-of-engineered life (SEEL) ships. The surrounding environment's environmental, health, and occupational safety aspects are particularly integrated with the process of ship dismantling. A plethora of previously published papers illustrated the challenges, opportunities, and advantages of utilizing more environmentally friendly and safer ship scrapping methods, especially for the leading ship recyclers situated in China, Turkey, and South Asia (Bangladesh, India, and Pakistan). This paper aims to review the existing literature on the occupational health and safety aspects of ship recycling across the aforementioned regions and compare the advances chronologically and regionally to find the research gaps. Through a scoping review using the databases of "Science Direct","Research Gate", and "Springer", this study compiles the current scenario of occupational safety standards existing among major ship dismantling destinations - India, Bangladesh, Pakistan, China, and Turkey for 17 years (2008-2024). To determine the general state of occupational health and safety (OHS) related to shipbreaking and ship recycling research, the most important articles were assessed for the review, and research gaps in hazardous waste management and the efficiency of workers' training were identified. These findings can be potential avenues for future study that could guide the development of the body of knowledge about SEEL ships and the OHS problems they raise.

Keywords: Occupational health and safety, Environment-friendly ship recycling, HAZMAT, Hong Kong Convention.

1. INTRODUCTION

Ship recycling is an indispensable phase in the life cycle of a vessel that enables the safe and environmentally responsible disposal of ships that have surpassed their lifespans. It entails removing a ship's structure and machinery to salvage valuable components and materials. Most ships last around 25 to 30 years before they may no longer be economically feasible for operational voyages. Yet, they still contain valuable materials that can be reused for multiple purposes. By breaking down ships, steel that would otherwise be discarded or left untreated can be recycled and used again for several purposes. Starting from assembling small-sized construction billets to forming sheet metals or iron rods, molten metal components, re-enforced bars, and other such secondary scrap sources, a ship also produces considerable amounts of non-ferrous materials, furniture, and wooden items, electrical appliances, and components, along with heavy machinery and digital accessories. Around 600 SEEL (safe-end-of-engineering life) ships are sent to disposal yards annually [1]. As per the current ship recycling market share, India, Bangladesh, Pakistan, and Turkey are among the significant global ship recyclers. Interestingly, due to low labor wages and less stringent adherence to occupational safety and health, South-Asian beaches have become more popular destinations for the demolition of most of the World's vessels. According to the World Bank and YPSA reports, about 50,000 people are working at shipbreaking yards in Bangladesh directly, with an additional 100,000 to 200,000 people working indirectly [2].

Despite being a common practice for centuries, the ship recycling process has recently drawn more attention due to growing concerns about the process's potential effects on the environment and workforce safety. As stated above, ship recycling is now principally performed across South-Asian beaches in India, Bangladesh, and Pakistan, where ships are landed at high tides on the sandy shores and scrapped down by private ship recyclers, most of whom are less aware of the occupational health and safety standards for a heavy labor-centric industry like ship recycling. Also, the intervention of the Govt. agencies towards rigorous monitoring of health and safety standards is somewhat flexible or absent in a few cases. Recycling a ship is complex and intricate, requiring planning, preparation, dismantling, and disposal of the ship's parts. Ship cutting and transfer, storage, and overall management of all sorts of materials are the two main working procedures in ship recycling facilities. Both of these processes require thorough planning, process preparation, emergency response, preparedness and safe operational plans, and efficient management of resources. Unfortunately, most of the South-Asian ship

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Received on 12-07-2026 Accepted on 16-08-2026 Published on 21-08-2026

recyclers do not abide by the proper regulations for compliant ship recycling, as a result of which several cases of fatal accidents and unanticipated injuries have taken place over the years in ship recycling destinations of South Asia.

Regardless of the potential benefits of ship recycling, the process poses several challenges, including the safe handling of hazardous materials such as asbestos, heavy metals (Pb, Cd, Hg), PCBs, and other HAZMATS (hazardous materials) in association with the proper disposal of waste, and the protection of workers' health and safety. Apart from heavy metals and PCBs, a range of hazardous and toxic substances, including glass wool, thermocol, oily rags, oily sludge, oily sand, polyaromatic hydrocarbons (PAH), and organotins like tributyltin (TBT), are recovered from old ships [3]. Moreover, the ship recycling industry, particularly in South Asia, has been criticized for its poor working conditions and environmental practices. When operating in confined spaces, major accidents happen due to lack of safety precautions, including not having gas monitoring or testing devices, not using safety suites, and ineffective ventilation, etc. Inadequate gas freeing and monitoring techniques while cutting plates from cargo ships create major fire threats that endanger personnel. In shipbreaking yards, minor mishaps like bruising, broken bones from moving heavy metals, and cuts from sharp edges frequently happen on occasion. In the shipbreaking industry in Bangladesh, neglecting first aid, emergency exits, emergency response, and rescue is also widespread. The prime accidental cause is the explosion of leftover gas and fumes in the tanks, and falling from high heights is also one of the major accidents [4]. Over the past decade, several workshops, international conferences, and seminars have raised the impoverished health and safety issues persistent in the ship recycling facilities of South Asia, particularly Bangladesh. Since then, there has been growing awareness across the community and pressure on the industry to improve the safety and environmental soundness of ship recycling [5]. To satisfy the requirements and expectations of various ship recycling stakeholders, national and international regulatory frameworks and standards are being developed or implemented. Already, India, China, and Turkey have progressed in this sector as they have established compliant recycling yards [6].

In South Asia, India is the pioneer among the three South-Asian nations in accepting and achieving international compliance in ship recycling activity. 115 ship recycling facilities in India are already certified as green ship recycling facilities and have achieved the Statement of Compliance (SoC) from the International Classification Societies, notably IACS members like ClassNK, Lloyd's Register, RINA, and IRS [7]. Bangladesh's government ratified the HKC in June 2023, and with this ratification, the HKC was globally enforced in June 2025. There are now 17 ship recycling facilities in Bangladesh that are SoC-certified [8]. On the contrary, Pakistan is going through an economic crisis, and it seems that the development of Pakistani ship recycling facilities is still a long way away. Currently, 2 Pakistani ship recycling facilities are SoC certified [9]. Aliağa, Turkey, is one of the major shipbreaking sites where a significant portion of the world's fleet was scrapped between 1994 and 2002. The recycled steel from Aliağa contributes significantly to Turkey's steel supply, although environmental and occupational health concerns have been addressed not long ago.

This review paper aims to provide a comprehensive and meticulous analysis of existing literature on ship recycling practices in major facilities from an occupational safety and health perspective. Specifically, it focuses on comparing ship recycling methods employed in prominent facilities, particularly in South Asia (India, Bangladesh, and Pakistan), alongside insights from China and Turkey. The objectives include assessing regulatory frameworks and standards, analyzing environmental and occupational health and safety impacts, and identifying research gaps to enhance occupational standards in these ship recycling destinations. This article also discusses research papers on occupational health and safety practices in these regions, followed by a thorough regional and chronological comparative analysis to pinpoint research gaps and opportunities for further investigation.

2. SHIP RECYCLING METHODS IN SOUTH ASIA, CHINA, AND TURKEY

The process of ship recycling begins with the ship being dismantled and brought to the recycling destination. Once the end-of-life (EOL) ship arrives at the recycling state, the dismantling starts with bringing the vessel as close as possible to the ship recycling facility. This is commonly done in European and North American ship dismantling facilities using the dry-docking or berthing method. For dry-docking, the ship is navigated into a dock, where the water is subsequently drained out, creating a dry environment for the dismantling process. Workers then proceed to deconstruct the vessel, removing its components piece by piece. Once the dismantling is completed, the dock undergoes a thorough cleaning to remove any debris or hazardous materials. Finally, the dock is refilled with water, making it ready for processing on the next vessel [10]. Due to strict government or territorial regulations, facilities in the EU, North America, and

China have adopted the above techniques, which are quite expensive to build and maintain. In Turkey, the landing method or slipway-based ship cutting is followed. But in countries like India, Bangladesh, and Pakistan, the berthing or dry-docking techniques and other methods like pier-breaking or slipway-based ship recycling are not followed since these infrastructures are not cost-effective.

The ship recycling facilities in South Asia utilize their beaches to carry out ship recycling via a more conventional and old-age tradition of bringing the ships as close as possible to the sandy shores of the beach within the facilities. This method is known as 'the beaching method.' The term beaching is commonly applied to shipbreaking at the beach in the intertidal zone [11], and intertidal landing is the official term that the practitioners of ship recycling use to indicate the beaching method. A beaching master carries out the process of beaching. The time is often set for beaching based on the moon's position and ideal high tide conditions. Most of the time, when a ship beaches itself, the engines are typically running and capable of operating at full capacity. Maximum operational speed is focused on towing the ship as close as possible to the yard's location when the engine is running at full power. Tugboats rarely pull the ships toward the coasts when their engines are not running. In this instance, near about four cables are linked to the ship's stem, two on each side, to pull the ship closer to the yard, and winches are used concurrently to tow the ships.

As the government and other associated national and local bodies have provided flexibility to the ship recycling facilities in using the method of beaching for ship dismantling, these countries (Bangladesh, India, and Pakistan) thus solely rely on this technique, which is not at all costly and offers substantial leverage for ease of ship recycling within the facilities. One significant matter concerning the ship recycling activity in South Asia that needs to be understood is that these nations opt for low-cost and fast-processed ship dismantling, for which the beaching method is ideal and ensures smooth production for dismantling operations. Typically, the working conditions and quality of life for ship-breaking laborers in these countries are poor, and the regulations to ensure workers fair wages and protect their well-being on the job site are not enforced in this area, which allows these beaching operations to continue [12].

In China, the process of ship dismantling occurs alongside quays or piers, and this method is called the alongside technique, or pier-breaking or the floating method. Some EU ship recycling facilities also use this method. This location choice simplifies ships' transportation to the recycling sites for dismantling. Unlike the beaching method, where ships are deliberately run aground and dismantled on the shore, the alongside method involves dismantling the ships in a process resembling the shipbuilding operation's reverse. Essentially, ships are taken apart systematically, similar to how they were constructed, rather than being cut into pieces. This method allows for more controlled and organized dismantling processes, potentially reducing environmental and safety risks associated with shipbreaking activities [13].

In Aliaga's coastal region of Turkey, ship recycling yards utilize slipways for bringing vessels ashore, a method known as the landing approach or slipway technique, which is a nontidal beaching method. In 2006, the landing areas of Turkey's ship recycling yards were mainly soil-based. However, changes have occurred over time, with the introduction of concrete flooring. The incorporation of concrete flooring indicates efforts to improve the infrastructure of these facilities, although the specific standards maintained for constructing these floors remain undisclosed [14].

In conclusion, the diverse methods employed for ship recycling and dismantling across different regions underscore the complex environmental implications associated with these processes. While South Asian countries such as Bangladesh, India, and Pakistan predominantly rely on the beaching method due to its cost-effectiveness and operational efficiency, concerns persist regarding these facilities' environmental and occupational safety standards. The use of slipways in Turkey's ship recycling yards reflects efforts to enhance infrastructure and possibly mitigate environmental impacts, although the specifics of these improvements remain unclear. In contrast, China's alongside method offers a more controlled and systematic approach to ship dismantling, potentially reducing environmental and safety risks. Despite these variations, the overarching concern remains the need for stringent regulations and enforcement mechanisms to address environmental pollution, worker safety, and community well-being in shipbreaking and recycling operations globally.

3. INTERNATIONAL CONVENTIONS AND GUIDELINES GOVERNING SHIP RECYCLING

Ship recycling regulations aim to ensure the decommissioned ships' safe and environmentally sound disposal. Since the End of Engineered Life (SEEL), ships became a matter of concern for the World, and specific regulatory frameworks or regulations became necessary to be developed to control the overall aspects of handling obsolete ships for scrapping purposes. Thus, the following regulations, among many others, have been taken over the past years:

- International Maritime Organization (IMO) Guidelines on Ship Recycling: The IMO provides guidelines to assist countries in implementing the Hong Kong Convention. These guidelines cover various aspects, including the safe and environmentally sound management of hazardous materials on board ships, training of workers, and facility requirements for ship recycling yards. The IMO's involvement in ship recycling began at the 44th MEPC session in 2000, leading to the establishment of guidelines on ship recycling, which were finalized and adopted by 2003. By 2005, the IMO recognized the need for a legally binding global instrument on ship recycling, prompting the development of regulations to ensure safe, environmentally sound practices throughout a ship's lifecycle. This effort culminated in the creation of the Hong Kong Convention, with extensive input from IMO Member States, NGOs, the International Labour Organization, and the Basel Convention.

- European Union (EU) Ship Recycling Regulation: The European Union (EU) Ship Recycling Regulation, Regulation (EU) No 1257/2013, was adopted to ensure that ships flying the flags of EU member states are recycled in a safe and environmentally sound manner. It mandates that large commercial seagoing vessels maintain an Inventory of Hazardous Materials (IHM) throughout their operational life, which certified inspectors must verify. A crucial aspect of the regulation is the establishment of the "European List" of approved ship recycling facilities, which must meet stringent safety and environmental standards. Before recycling, a specific Ship Recycling Plan (SRP) must be developed and approved, detailing how the ship will be dismantled safely. The regulation requires both ships and recycling facilities to be certified and authorized, and EU member states are responsible for enforcement through regular inspections. The regulation aligns with the Hong Kong International Convention, but it extends requirements to all ships entering EU ports, irrespective of their flag state, effective from December 31, 2020. This ensures a higher standard of global ship recycling practices. By implementing these measures, the regulation aims to mitigate the adverse effects of ship recycling on human health and the environment, promoting safer working conditions and better waste management. The overarching goal is to enhance the sustainability and safety of ship recycling operations globally.

- Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal: The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, adopted in 1989, is a key international treaty regulating the movement and disposal of hazardous wastes, including those generated by ship recycling. It aims to protect human health and the environment from the adverse effects of hazardous waste. In the context of ship recycling, the Convention addresses the issue of ships containing hazardous materials being sent to developing countries for dismantling, where safety and environmental standards may be lax. The Basel Convention requires prior informed consent from receiving countries before hazardous wastes can be transported across borders. It promotes environmentally sound management practices for hazardous waste disposal, ensuring that ship recycling activities are conducted safely. Additionally, the Convention provides a framework for member countries to develop policies and strategies to minimize hazardous waste generation and improve waste management. Compliance with the Basel Convention helps mitigate the negative impacts of ship recycling on both workers and the environment.

- Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (2009): The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, adopted in May 2009, ensures that ships being recycled do not pose unnecessary risks to human health, safety, and the environment. Developed with input from the International Maritime Organization (IMO) Member States and non-governmental organizations, and in cooperation with the International Labour Organization and the Basel Convention parties, the Convention mandates several vital provisions. Ships must maintain an Inventory of Hazardous Materials (IHM) to ensure safe handling during recycling. Recycling facilities are required to develop a specific Ship Recycling Plan (SRP) for each ship, outlining safe and environmentally sound recycling processes. The Convention emphasizes worker safety by mandating adequate training and the provision of personal protective equipment (PPE). Regular inspections and certifications are required to ensure compliance with safety standards. Health surveillance of workers is mandated to monitor and prevent occupational

health issues. Facilities must also establish emergency preparedness and response plans to address accidents and hazardous material releases. These measures aim to minimize risks associated with ship recycling activities and enhance overall occupational health and safety standards in the industry. By implementing these protocols, the Convention seeks to promote safer and more sustainable ship recycling practices globally.

- Local/National Occupational Health and Safety Guidelines: Ship recycling facilities must adhere to various occupational health and safety guidelines, such as those issued by the International Labour Organization (ILO). These guidelines cover areas like safe working conditions, training and qualifications of workers, personal protective equipment, and emergency preparedness. It is important to note that specific regulations may vary between countries or regions. Therefore, it is advisable to consult the regulations applicable to the specific jurisdiction where ship-recycling activities are taking place. In Bangladesh, the principal authority governing ship recycling regulations is one government body (the Ministry of Industries). This organization has two established guidelines for shipbreaking activity within the territory of Bangladesh, respectively, the Ship Breaking and Recycling Rules, 2011, and the Ship Breaking Act, 2018. Likewise, in India, the Gujarat Maritime Board is the authority that regulates ship recycling and maintains the issues of economic, environmental, and occupational safety. In Turkey, the Ship Dismantling Regulation serves as the main regulatory framework governing ship recycling operations, complemented by several other domestic regulations such as the Environmental Law, Occupational Health and Safety Law, and Regulation on Health and Safety Measures in Working with Asbestos [14].

Despite the existence of these conventions and guidelines, ensuring their effective implementation faces significant challenges. One major issue is the insufficient resources and capacity in many developing countries, which are primary locations for ship recycling activities. These countries often lack the necessary infrastructure, funding, and technical expertise to fully comply with international standards. Another challenge is the disparity in regulatory enforcement across different nations. Some countries have stringent regulations and rigorous enforcement mechanisms, while others have more lenient rules and oversight. This creates an uneven playing field, making it difficult to achieve uniform safety and environmental standards globally. The discrepancies in regulations can lead to competitive disadvantages for countries with stricter guidelines, potentially driving shipowners to choose facilities with lower compliance costs, thus undermining the overall objectives of the conventions. Consequently, addressing these challenges requires coordinated international efforts to build capacity, harmonize regulations, and ensure equitable enforcement across all ship recycling nations.

3.1. Implementation of the Hong Kong Convention and its Contribution to Sustainable Ship Recycling

The instruments described above differ considerably in their maturity of implementation, and the Hong Kong Convention warrants particular attention because its transition from an adopted but dormant instrument to an operative one occurred within the period covered by this review. Adopted in May 2009, the Convention remained unenforceable for over a decade owing to its tripartite entry-into-force criteria, which required ratification by fifteen states representing forty per cent of world merchant shipping by gross tonnage and a combined annual ship recycling volume equivalent to three per cent of the tonnage of the ratifying parties, as per an IMO report [15]. The accession of Bangladesh in June 2023 satisfied the outstanding conditions, and the Convention accordingly entered into force on 26 June 2025. The significance of this sequence is that the threshold was crossed not by flag states but by a principal recycling state, which locates the burden of implementation squarely within the South Asian yards that this review examines.

Implementation of the Convention operates through two interlocking obligations, one attaching to the ship and one to the facility. On the vessel side, the Inventory of Hazardous Materials establishes a documented account of asbestos, heavy metals, polychlorinated biphenyls and other regulated substances present in the structure, maintained and verified across the operational life of the ship rather than compiled at the point of disposal. On the facility side, the Ship Recycling Plan requires each yard to specify, in advance and for each individual vessel, the sequence of dismantling, the handling and storage arrangements for hazardous materials, and the emergency preparedness provisions applicable to the operation. The regulatory logic connecting the two is anticipatory rather than reactive: hazards are identified, located and planned for before cutting begins, in contrast to the prevailing practice in which the composition of a vessel is discovered during dismantling.

Evidence of implementation at facility level, however, remains markedly uneven across the five

nations reviewed. India has advanced furthest, with 115 yards holding Statements of Compliance issued by IACS member societies including ClassNK, Lloyd's Register, RINA and IRS, indicating that documented recycling planning and third-party verification has become an established practice at Alang. Bangladesh, despite having been the state whose accession brought the Convention into force, has only 17 certified facilities, a figure that stands in stark disproportion to a workforce estimated at 50,000 direct and up to 200,000 indirect participants. Pakistan has only 2 certified facility, and the constrained economic conditions described earlier make near-term certification unlikely. Turkey and China approach compliance from a different starting position, since their landing and alongside methods already provide much of the containment infrastructure that certification presupposes. The pattern indicates that ratification and operational compliance are separated by a considerable interval, and that the Convention's entry into force marks the beginning rather than the conclusion of the implementation process.

Two structural limitations qualify what compliance can be expected to deliver. First, the Convention establishes performance requirements for safe and environmentally sound recycling without prescribing the dismantling method by which they are met, whereas the European Union Ship Recycling Regulation specifies impermeable flooring and effective drainage as conditions of listing. Facilities operating on the intertidal zone may therefore satisfy the Convention while remaining outside the European List, producing a two-tier compliance environment in which the applicable standard depends on the flag a vessel happens to fly at the point of sale. Second, the effectiveness of certification depends upon the frequency and independence of verification, and the reviewed literature contains little assessment of whether certified status corresponds to sustained rather than episodic conformity — a gap identified in Section 6 and one that acquires greater urgency now that certification carries legal consequence.

Notwithstanding these qualifications, compliance contributes to sustainable ship recycling and safer maritime operations through several identifiable pathways. Occupationally, the mandated provision of training, personal protective equipment, health surveillance and emergency response addresses precisely the failure modes that recur throughout the studies reviewed in Section 5, namely residual gas explosions during hot work, uncontrolled falls, and the absence of first aid and rescue capability. Environmentally, the Inventory of Hazardous Materials functions as the informational foundation for downstream waste management, since hazardous streams cannot be segregated, treated or consigned to licensed disposal unless their presence and quantity are known in advance. Economically, the requirement that ships carry a verified inventory throughout their service life extends the regulatory reach of the Convention backwards into design, construction and operation, encouraging substitution of regulated materials at the point of specification rather than remediation at end of life. Collectively, these mechanisms reposition ship recycling within a circular materials economy, in which the recovery of steel and non-ferrous metals is conditioned upon the safe treatment of the hazardous fraction accompanying it, rather than achieved at the expense of the workforce performing the recovery.

4. METHODOLOGY

This study has conducted a scoping review of ship recycling and shipbreaking with a focus on health and occupational safety in particular. The study has been planned to present the scenario of ship recycling in South Asia, China and Turkey with importance on the aspects of environmental and occupational health and safety. For carrying out the literature review, a scoping review approach has been used. A set of keywords was put in specifically to carry out the review. This scoping review was conducted using the PRISMA-ScR guidelines. The search strategy included the following databases: Science Direct, Research Gate, and Springer. Other databases like Scopus, Web of Science, and JSTOR could not be accessed without a paid subscription from Bangladesh, where this article was produced, hence, the three above databases were chosen. The search terms included "ship recycling," "shipbreaking," "ship scrapping", "occupational health," and "safety." The time frame for the search was 2008-2025. Articles were included in the review if they met the following criteria: (1) they were published in a peer-reviewed journal, (2) they focused on occupational health and safety in ship recycling, and (3) they were written in English. Posters, presentations, Theses, Books, and other preprints were not included in this review.

Data were extracted from the included articles using a standardized data extraction form. When "ship recycling," "shipbreaking," and "ship scrapping" were used in the search string, 104 results were generated. But, three separate words, ship and recycling and shipbreaking resulted in generating 150 documents. Of these, 125 articles comprised research and review-based articles, and the remaining 25 articles fell under the categories of books, book reviews, encyclopedias, and editorials. During this timeframe, 2025 alone had the highest number of articles, while 2009 and 2011 did not show any published article.

Since the scope of this review paper is confined to specific and narrowed-down literature, particularly focusing on the health and safety arena integrated into the process of ship recycling and ship breaking, these two keywords were provided as inputs to confining the searching using the following keywords – 'shipbreaking health and safety' and 'ship recycling occupational health and safety'. On that basis, a total of 53 articles were obtained. All these articles have demonstrated scientific findings based on ship recycling and ship-breaking scenarios in South Asia, China, and the European Union (EU) countries. Of these 53 articles, 43 articles presented the analysis of ship recycling and shipbreaking with regard to impacts, investigation, novel approach, and other factors of occupational and environmental health and safety. The other 10 articles indicated economic, policy-level, and legal aspects of ship recycling and shipbreaking. Hence, these documents were not considered for review in this study.

To scrutinize the published articles for review, three more keywords were incorporated, respectively 'occupational health' and 'safety' connected with the word ship recycling. But interestingly, on enlisting the following words together – ship recycling, occupational health, and safety- 527 articles were obtained, of which there were 369 research articles and 158 review articles. From these articles, only 43 articles were listed that specifically highlighted research on the occupational safety and health factors associated with ship recycling activity.

The remaining 484 articles were focused on the legal aspects of shipbreaking, circular economy, electronic-wastes, battery and chemical wastes, environmental aspects, and subjects non-relevant to ship recycling and occupational safety. Among these 484, some articles were also based on Norway, other EU countries, Brazil, Egypt, Indonesia, and Vietnam, which was not consistent with the scope of this particular review paper. Hence, 43 articles, along with their key research findings, citation numbers, list of authors, and article titles according to the year of publication, have been tabulated at the concluding end of this manuscript.

In addition to highlighting the key findings, this review also connected the research aspects (country-wise) of the 43 papers categorized (occupational health and safety only) and discussed the similarities in the collective studies, the essential results, facts, recommendations, and the research gaps. Figure **1** presents a step-by-step framework for conducting the systematic literature review based on the search string method.

4.1. Country-Wise Distribution of Research

Shipbreaking and ship recycling industries have grown for over 70 years now. Earlier, mechanized and developed countries adopted ship dismantling. Gradually, from the 1980s, with stricter environmental and legal restrictions being applied in the modern world, developed countries could no longer sustain shipbreaking, and eventually, the least-developed

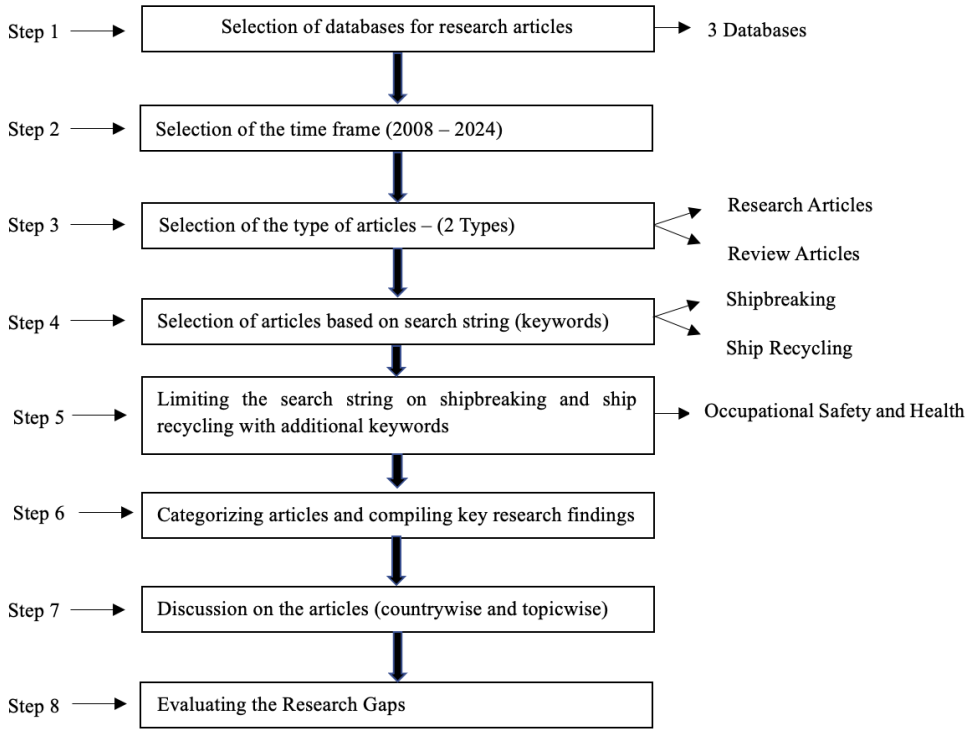

Figure 1: Method-oriented framework for conducting the systematic literature review.

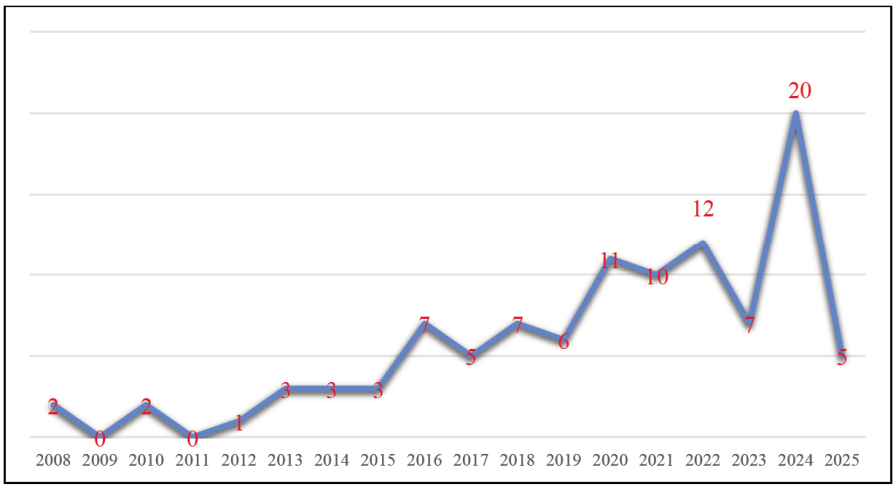

Figure 2: Distribution of articles published from 2008 to 2025 in shipbreaking and ship recycling.

countries overtook. Other developing nations centered along the South and Southeast Asian territory became the hub for ship dismantling and ship recycling. Accordingly, over the past three decades, several research studies have been conducted, and scientific publications have been developed in the field of shipbreaking and ship recycling. Figure **2** illustrates a graphical distribution of published research and review articles from 2008-2025. It can be seen that research has continued to rise in this field since 2016, and post-pandemic, the number of published articles is higher. The major contributing articles mostly highlight research work based on the shipbreaking and ship recycling industries located in the Indian subcontinent, specifically India and Bangladesh. Apart from the research published by Indian subcontinent authors, much research has been carried out for Turkey and China. These researches have contributed to ship recycling typically in three stages – economic aspects and ways forward, environmental issues, and investigations concerning the derivable hazardous elements, the occupational safety and health considerations of the ship recycling industry workforce, and its connected training and legal monitoring aspects.

The region or country-wise distribution of the reviewed articles in shipbreaking and ship recycling focused on human factors and occupational safety and health is presented in Figure **3**. It shows the distribution of the number of published articles focusing specifically on the major ship recycling nations, – India, Bangladesh, China, Pakistan, and Turkey, as per the database-generated search outcomes for 43 articles. Bangladesh has the highest number of research, and there are a few Indian articles specifically where both the countries (India and Bangladesh) have been mentioned together and there are case studies or qualitative and quantitative information in the same articles. India has produced some quality research in this field, particularly outlining the occupational safety and health aspects. Some Pakistani and Chinese ship recycling industry-oriented articles have come jointly with the elaboration of both the Indian and Bangladeshi perspectives on the same manuscript. However, Turkey and China have separate research only catering to the case studies based on the Turkish and Chinese ship recycling industries. Turkey and India have substantial research on the core factors of occupational safety and health, but Pakistan's ship recycling research works are quite less compared to

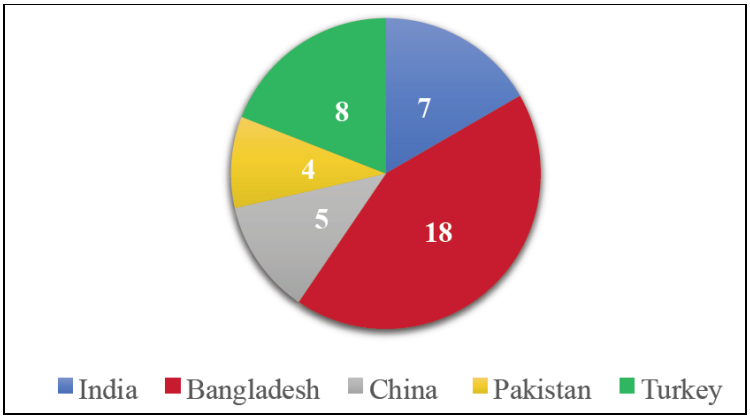

Figure 3: Distribution of the number of reviewed articles focusing on the major ship recycling nations – India, Bangladesh, China, Pakistan, and Turkey.

the Turkish, and Indian publications. Out of the 43, 01 article focused on global shipbreaking and does not reflect on any specific country, so the data projects countrywise distribution for 42 articles.

5. DISCUSSION

The paper mainly reflects on two parts under this section. In the first segment, a structured overview is presented pertaining to the available research on health issues and occupational safety for all the five listed countries with key information extracted from the published articles. The second segment shows the country-wise key research findings in tabular format.

5.1. Existing Research on Health Issues

5.1.1. Exposure to Asbestos

When it comes to analyzing the issue of hazardous wastes or HAZMATs existing within the ship recycling industry, the most common HAZMAT items that have been a cause of concern for affecting the human lives involved with the ship recycling job include notably asbestos and glass wool. Asbestos and glass wool have been utilized as insulating materials in industrial applications and structures for years. Their widespread use can be attributed to their unique properties, including resistance to heat, acids, and chemicals, as well as their high flexibility and tensile strength. Thompson *et al*., [16]. When ships are dismantled, the fibers can become airborne and inhaled, leading to serious conditions such as asbestosis, lung cancer, and mesothelioma. Even brief exposure to asbestos can have long-term health effects.

As per an Alang case study, statistical data were collected for a total of 241 dismantled ship surveys over 2 years. 7 types of ships for dismantling were surveyed during this time. Around 10 million LDT was the cumulative figure during this time for 809 dismantled ships. 15 types of waste were generated and identified during this time. The most probable locations of finding asbestos, asbestos-containing materials (ACMs), and glass wool on board were identified. These areas and surfaces are marked before recycling an EOL vessel beached in Alang yards (India) Hiremath *et al*., [3]. In another study carried out across Alang (India) to evaluate the existing methods of managing asbestos and glass wool wastes, the procedures of ship dismantling were examined. For the yards to better demonstrate compliance with Indian and international norms, proposals and interventions have been outlined in the form of a framework for managing asbestos and glass wool wastes generated by the yards [17]. Inductively Coupled Plasma-Atomic Emission Spectroscopy and Scanning Electron Microscopy approaches were carried out in this study to assess the color, odor, moisture, ignition, and contaminants involved. According to the authors, the presence of phthalates poses a serious threat to the marine ecosystem and is thought to be a possible endocrine disruptor. A study highlighted the assessment of mesothelioma disease associated with long-term and past asbestos exposure [18]. According to this study, mesothelioma mortality risk was estimated using the Berman and Crump equations. The authors concluded from the results that 1841 total deaths are anticipated for 2017, and 4,515 mesothelioma-related deaths are anticipated for the entire period, which is about 15% of all employees employed in 1994. The maximum number of deaths is anticipated to occur in 2027, with a sharp rise in the anticipated death toll between 2012 and 2017.

Rabbi and Aevelina, 2017 [4] identified workers' rights, and workers' safety violation-oriented problems within the shipbreaking industry of Bangladesh. According to the authors, exposure to POPs and particles such as asbestos harms both the environment and human health. The causes of cancer are linked to asbestos contamination within the shipbreaking facilities.

The study by Wu *et al*., 2014 [19] examined the probability of increased risks of cancer among the male shipbreaking workers of Taiwanese shipbreaking yards across a 24-year period. A total of 4155 male workers were studied between 1985-2008 for new evaluating cancer cases caused due to exposure to asbestos-containing materials. The age (5-year intervals) and calendar time-specific yearly rates of cancer incidence with reference to the general population of Taiwan from 1985 to 2008 were used to determine the anticipated number of cancers among shipbreaking personnel. Relative risk estimates were computed using standardized incidence ratios (SIRs). For shipbreaking workers having Total Exposure Potential Scores for asbestos, the cancer hazard ratio (HR) was computed. 3 different types – general cancer, oral cancer, and respiratory cancer were found among 504 workers, and mesothelioma was found to be prone among flame-cutting workers over a 5-year latency period. The group with the highest asbestos exposure was linked to a higher SIR for both oral and total cancer, irrespective of either a 5-year or a 10-year latency period. The authors concluded that shipbreaking workers had higher rates of asbestos-related illnesses, such as mesothelioma and lung cancer, and some of these instances seemed to be dose-dependent.

5.1.2. Toxic Chemicals and Heavy Metals

Ships contain numerous toxic substances, including PCBs (polychlorinated biphenyls), mercury, lead, and chromium. Workers who handle these substances

without proper safety measures are at risk of poisoning, neurological damage, kidney damage, and long-term carcinogenic effects. Cadmium and benzene exposure are also common concerns, leading to cancer, reproductive issues, and organ damage. Deshpande *et al*., 2012 [20] carried out a study that used a novel technique to demonstrate the maximum heavy metal exposures for ship recycling yard workers at Alang (India). According to the method for the study, a mathematical model was developed using the Vector Addition Approach and Gaussian Dispersion technique. The Gaussian model for air pollution dispersion was modified to measure the pollutant concentrations along the centerline for each cutter conceived as a separate point source. Also, the mathematical modeling exercise carried out in this work served two purposes. The first step determined the range of influence the plume's effect had. The second step calculated the total highest concentration of heavy metals that could exist in a particular yard's environment. The findings from the study were that regardless of wind speed, the highest cumulative concentration of heavy metals remained relatively consistent, with the maximum concentration occurring 145 meters downwind from the first cutter. Their key finding was that cumulative maximum heavy metal concentrations were estimated between 113 g/Nm3 and 428 g/Nm3 at varying wind speeds. Additionally, lead (Pb) content in outside air was estimated between 8 and 30 g/Nm3, surpassing Indian National Ambient Air Quality Standards (NAAQS).

According to Hossain *et al*., 2016 [21], lead (Pb), mercury (Hg), cadmium (Cd), iron (Fe), aluminum (Al), zinc (Zn), copper (Cu), chromium (Cr), and manganese (Mn) are among the heavy metals linked to ship-breaking activities. These metals are highly concentrated in the sediment and seawater in the ship-breaking area of Chattogram. The study also states that PAHs, PCBs, organotins, asbestos, and other such atmospheric pollutants have been identified within the ship-breaking activity areas, which are directly responsible for causing cell damage and mutations, harming the immune system, causing cancerous diseases, neurological damage, and other such illness over prolonged periods due to exposure to such harmful substances.

A study by Rahman, 2017 [22] examined the environmental and health impacts of ship recycling in Bangladesh. The research highlighted the dangers posed by hazardous materials like PCBs, PVCs, PAHs, TBTs, oil, asbestos, heavy metals, isocyanates, and radioactive particles found in obsolete ships. Among heavy metals, lead poses the greatest risk, causing severe health issues such as neurological and physical development delays in children and impairing hearing, vision, and muscle coordination in adults. Lead also damages the reproductive system, heart, kidneys, and blood vessels. PCBs are toxic, bio-accumulate in the environment, and are linked to immune system dysfunction, cancer, liver damage, and reproductive problems. The incomplete combustion of PCBs can produce harmful dibenzofuran and dioxins. PVC inhalation can cause respiratory tract ulceration, while asbestos exposure can lead to lung cancer, mesothelioma, and asbestosis. Additionally, substances like TBTs, PAHs, and oil contaminate aquatic environments and nearby water bodies.

On the other hand, Alam *et al*., 2019 [23] conducted a study to assess the health risks of people engaged with ship recycling due to soil contamination by toxic pollutants and found some positive outcomes. Soil samples were collected and analyzed in this study to measure the concentration of 8 potentially toxic elements (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) using inductively coupled plasma optical emission spectrometry (ICP-OES) (iCAP 6300; Thermo Fisher Scientific, Waltham, MA). The results of the study showed that soil metal concentrations were comparatively higher for Cd, Cr, Cu, Mn, Ni, and Zn, with decreasing concentrations in the following order: Cd > Zn > Cr > Cu > Pb > Ni > Mn > As. The most contaminated SBRIs are those in Bangladesh's storage zone. Anthropogenic activities, such as ship dismantling and natural parent materials were two significant groupings of sources (identified by PCA and validated by correlation analysis) contributing to the observed concentration of PTEs in soil from SBRI in Bangladesh. The projected number of people in every 100,000 who were at risk of developing cancer from soil-contaminating PTEs was only 6 to 7 people. The authors stated that the possible cancer risks associated with As, Cd, Cr, Ni, and Pb were determined to be within acceptable levels. Only the evaluation of heavy metal contamination from the standpoint of shipbreaking operations in Bangladesh was covered in this study.

The amounts of four hazardous metals - arsenic, chromium, cadmium, and lead—in the water and sediments at the Sitakunda ship-breaking location in Bangladesh were investigated in the study [24]. Using an atomic absorption spectrophotometer, a total of 120 samples, 60 water samples and 60 sediment samples, were gathered and examined in the winter and summer. The amounts of these metals in both water and sediment were found to be higher than advised. Seasonal differences were observed in the levels of arsenic and cadmium but not in lead or chromium. With a high cumulative effect of metal concentrations, the Metal Pollution Index (MPI) and Contamination Factor (CF) showed critical water quality. Except for chromium, the Geoaccumulation Index (Igeo) indicated moderate

to severe pollution in the region. According to the CF, sediment samples had moderate to high levels of lead, arsenic, and cadmium contamination. All of the sampling sites inside the ship-breaking region showed high levels of heavy metal contamination, according to the Pollution Load Index (PLI). concern and Potential Ecological Risk Indicators demonstrated that the area's metal pollution posed a significant concern. Therefore, quick action is required to improve the region around the study areas.

The study Islam *et al*., 2023 [25] explored the impact of ship recycling activities on soil, crop quality, and human health in Bangladesh. From an area surrounding shipbreaking yards, soil and crop samples were collected, which disclosed elevated levels of various metals, including Cd, As, Pb, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Sn, Sb, and Tl. These contaminants pose potential health risks to the population. Cd, As, Mn, and Pb were identified as threats to adults who consume rice, and Pb, Cd, Tl, and Co pose risks through vegetable consumption. The PCA-APCS-MLR model spotted mixed anthropogenic (from shipwrecking operations) and geogenic sources as prime contributors to soil contamination (69%). Moreover, Industrial discharge, mostly from nearby ship recycling industries, contributes to about 24% of the contamination. The study also revealed spinach leaf and gourd as high-risk vegetables. Overall, the findings underlined the environmental threats posed by shipbreaking operations. Finally, it emphasized the need for management strategies to protect agroecosystems and minimize health risks.

From the results of the heavy metal analysis [26], most Aliaga samples were contaminated with Hg, Cd, Pb, Cr, Cu, Zn, Mn, and Ni. On the other hand, metal concentrations in sample points were found to be higher than background Mediterranean levels. The amounts of Hg, Pb, Cu, Zn, and Ni in Aliaga Bay exceeded the numerical TEL and PEL values. Otherwise, the Cr values were higher than the TEL values. Sediments that were contaminated with Pb, Cr, Cu, Zn, and Ni were deemed to be extremely polluted, whereas the SQG assessed Cd contamination in sediments as non-polluted. The metal pollution indexes showed that coastal stations had the highest MPI values. The metal pair ratios clearly showed the maximum enrichment of Hg, Cd, Pb, Cu, and Mn based on the enrichment factors. The authors concluded that the petrochemical complex, steel industries (iron smelters and roller mills), shipbreaking sector, and unmanaged shipping traffic are responsible for the highest concentrations of heavy metals. While the shipbreaking business uses lead, mercury, and cadmium, modern paints still include significant levels of zinc and copper.

In a study by Yılmaz *et al*., 2016 [27], sediment samples from five locations at the Aliağa Shipbreaking Yard along the Aegean Sea coast were collected to examine pollution levels caused by shipbreaking activities. The samples were analyzed for organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides (OCPs), and the result indicated concentrations ranging from 585 to 25,000 mg/kg in dry weight. Additionally, eight metals (Cd, Mn, Ni, Pb, Cr, Cu, Fe, and Zn) in the sediment samples were measured. Both pollutant levels were compared with sediment quality guidelines to evaluate potential effects on marine ecosystems. The results indicate high levels of organic and heavy metal pollutants in sediments at Aliağa Shipbreaking Yard, which refers to shortcomings in pollution management policies for such industries. Diagnostic ratios suggest that cutting operations during ship breaking may be responsible for pyrolytic sources of PAH compounds. Higher levels of PCB concentrations in sediments raise environmental and health concerns. Sediments also showed significant toxic levels of copper, lead, and zinc. The authors suggested the strict management of PCB inventory and the careful removal or dismantling of antifouling paints and electrical equipment containing these harmful metals. HAZMAT risks can be largely mitigated if the shipbreaking yards abide by international rules and regulations. Du *et al*., 2018 [28] conducted two case studies based on the green disposal of HAZMATs for two ship recycling facilities that have abided by the Hong Kong Convention and are certified via DNV-GL Class. The study evaluated the locations of HAZMATs in obsolete ships and their hazardous properties. Along with discussing properties, the authors have also pointed out the harmful effects of these hazardous materials on humans. The study later depicted the safe procedures to dispose of hazardous materials from the process practiced in two different ship recycling yards, where the two case studies were conducted in this study. The paper of Du *et al*., 2018 [28] reflects on the types and ways to dispose of hazardous materials derived from ship recycling facilities in China. Asbestos, PCBs, glass fiber, solid foam, waste oils, and other hazardous chemicals are frequently found in end-of-life ships. If these items are not managed properly, they could pose a safety and environmental risk. Different approaches to dealing with various types of hazardous materials already exist, but cutting-edge safeguards and strategies must still be developed to safeguard the environment and human health better. Sadly, while cost and quality are the primary considerations in ship design, the recycling

process is not considered. "Design for recycling" has emerged as a significant concern in other industries, such as the production of electronics and automobiles. The disposal of the primary hazardous materials at Jiang Men Zhong Xin Shipbreaking & Steel Co., LTD. and Jiangyin Changjiang Ship-Breaking Yard has been the subject of two case studies, according to this research. Both businesses have followed meticulous protocols and methods for recycling hazardous materials that could endanger workers and the environment. A significant finding of this study is that shipbreaking companies should fully utilize the Hong Kong Convention and European regulations, improve their technology, and change their management method for handling hazardous materials.

In another study by Hasan *et al*., 2023 [29], statistical analyses and Monte Carlo simulations were carried out to assess the health risks associated with exposure to significantly high levels of lead (Pb), cadmium (Cd), and arsenic (As) in the shipbreaking zone of Bangladesh. High concentrations of trace metals (Pb, Cd, Cr, Zn, As, etc.) have been found in soil sediments from the ship-breaking facilities of Sitakunda, Bangladesh, with most samples classified as very highly contaminated. Based on the cluster analysis, it has been found that these heavy metals primarily originate from anthropogenic sources related to ship-breaking activities. The geo-accumulation index, along with enrichment factors, confirmed sediments were heavily enriched with Pb, Zn, and As, and almost 2 out of every 100,000 individuals at the shipbreaking yards might develop cancer due to exposure to these trace metals. Through ingestion and dermal absorption, these metals can result in carcinogenic health risks among the workforce, which was confirmed based on the Total Carcinogenic Risk (TCR) values.

5.1.3. Physical Injuries

Shipbreaking is physically demanding work. Workers often engage in manual cutting, welding, and lifting heavy objects, increasing the risk of musculoskeletal injuries, burns, cuts, and even fatalities. The industry has a high rate of workplace accidents due to the hazardous and chaotic nature of the work environment.

Labor safety lax, health problems, and environmental problems have been categorized in a study conducted by Zakaria *et al*., 2012 [30]. According to the findings of this study, non-compliance with safety issues during cutting operations causes various kinds of accidents. A few issues, like improper plate cutting sequence, not following plate cutting standardized techniques, and carrying heavy plates without safety precautions, pose threats for harming the lives of the workers. Falling off heavy objects is a common form of safety problem in ship recycling yards in Bangladesh. Also, falling from high heights due to not practicing the safety standards of wearing safety belts and helmets is a common scenario. During plate cutting, due to not preparing the surface while plate cutting and while working in confined spaces, as well as not following proper safety measures and arranging for ventilation, serious accidents occur. Additionally, there are issues like the inadequacy of emergency action and rescue and first-aid support. The authors have stated that fire explosions, especially for oil tankers, are one of the major reasons for frequent fatal accidents in Bangladesh. Patwary *et al*., 2019 [31] outlined occupational safety lapse issues within the ship recycling industry of Bangladesh, including the occurrence of frequent accidents like falling from heights, cuts, and injuries, explosion-based injuries, and confined space entry accidents.

5.1.4. Respiratory Issues

Workers are at high risk of developing respiratory diseases due to exposure to dust, fumes from welding and cutting, and toxic gases. Chronic obstructive pulmonary disease (COPD), bronchitis, and pneumoconiosis are some of the common respiratory issues seen in workers in ship recycling yards. Qayum and Zhu, 2018 [32] outlined a study to demonstrate the shipbreaking industry of Pakistan and its related effects on marine life and humans. This qualitative discussion-based work highlighted the negative impacts of POPs, asbestos, and all toxins like PCBs, TBTs, heavy oils, PAHs, PVCs, etc. The lethal effects of such toxic substances on the lives of the workers associated with shipbreaking have been articulated. The troubles include respiratory diseases, cancerous diseases, and other long-term health complexities that may burden shipbreaking workers due to not having adequate safety facilities.

5.2. Existing Research on Occupational Safety

5.2.1 Poor Working Conditions

Many ship recycling yards operate in unsafe and unhygienic conditions, with inadequate sanitation, poor ventilation, and limited access to medical care. These conditions contribute to the spread of infectious diseases and mental health issues, including stress, anxiety, and depression due to the uncertainty and physical toll of the work.

The findings of Zakaria *et al*., 2012 [30] indicated non-compliance with safety issues during cutting operations in Bangladeshi shipbreaking yards, which causes various kinds of accidents there. A few issues, like improper plate cutting sequence, not following

plate cutting standardized techniques, and carrying heavy plates without safety precautions, pose threats for harming the lives of the workers. Not preparing the surface while plate cutting and while working in confined spaces, not arranging for ventilation are reasons behind serious accidents. Also, falling from high heights due to not practicing the safety standards of wearing safety belts and helmets is a common scenario. Furthermore, there are issues like an inadequacy of emergency action and rescue and first-aid support. The authors have stated that fire explosions, especially for oil tankers, are one of the major reasons for frequent fatal accidents in Bangladesh. According to Rabbi and Aevelina, 2017 [4], multiple deaths have occurred due to explosions, falling off heavy plates from high heights, not following proper safety guidelines, and using PPEs or safety devices in Bangladesh. Also, workers are deprived of their rights when victimized by such accident situations. The authors also reflected on the consequences of accidents occurring within the ship-breaking facilities, which mainly include serious fire hazards due to improper gas freeing and gas monitoring procedures and other minor accidents like brushing, broken bones while carrying heavy metals, and cutting due to sharp edges while working inside the ship-breaking yards.

In a study conducted by Arslan *et al*., 2013 [33], dust, cold, working near moving things, welding fumes, open fire, and carrying and lifting big objects were among the top job dangers mentioned by Turkish ship dismantling employees. The most typical injuries are directly correlated with these dangers. Hazardous materials, working at heights, oil/fuel spills, explosive gases, and snapping of ropes/wires have all been associated with a lack of identification.

5.2.2. Lack of Personal Protective Equipment (PPE)

Many workers do not have access to or cannot afford adequate PPE, such as masks, gloves, and protective clothing. This significantly increases the risks of exposure to harmful substances and physical injuries. According to Zakaria *et al*., 2012 [26], while at work, a lack of proper safety equipment or PPEs leads to the inhalation of toxic gases and eye injuries. The study of Hossain, 2015 [34] discussed the improper use of safety equipment and PPE, which is a common scenario among the workforce engaged in ship recycling in Bangladesh.

5.2.3. Lack of Health and Safety Regulations

In many countries where ship recycling is prevalent, there are insufficient regulations or weak enforcement of health and safety standards. This leads to a lack of proper worker protection, inadequate training, and unsafe working environments. The study by Tanha *et al*., 2022 [35] investigated the accuracy of this notoriety by examining how different shipbreaking yards maintain workplace safety. Data were collected using in-depth case-based research from government representatives, industry experts, and NGOs at three shipbreaking firms in Chattogram Bangladesh with the help of interviews, site visits, and industry reports, Safety performance data, including the number of injuries and fatalities, were collected between 2014 and 2019 and verified from various sources. Contrary to the expectation of uniformly poor outcomes, the findings reveal better but varying workplace safety practices among the three shipbreaking firms. The firms with better safety results demonstrated higher managerial commitment to improving safety, provided personal protective equipment (PPE) and training, implemented formal management systems, and had stronger management processes regarding workplace safety.

Saha *et al*., 2013 [36] published an article showcasing the dangers posed by toxic substances and the urgent need for improved occupational safety and health practices in light of the available data on accidents and injuries from 2001 to 2012 in Bangladesh. The study evaluated risks based on 12 types of hazards existing within the shipbreaking industry with the frequency of occurrence and the reasons for occurrence, which indicated the absence of safety regulations in the shipbreaking industry, contributing to unsafe working conditions. For the betterment of the industry, the authors proposed several safety recommendations and the strict enforcement of zoning, Govt. intervention, the Owner's responsibility, and the adoption of a comprehensive OSH management system.

Ahmed and Siddiqui, 2013 [33] carried out a qualitative study on the shipbreaking industry of Pakistan, highlighting the problems and prospects. The paper contains a very brief discussion regarding the rules and regulations adhering to the health and safety aspects which are not very strict in the context of Pakistan.

China, however, has made some notable changes in terms of ensuring safety regulations in shipbreaking yards. As per the findings of this study conducted by Du *et al*., 2017 [13], the Chinese ship dismantling facilities have already incorporated structural changes in terms of environmental safety management. Along with maintaining complete rules and regulations, the ship recyclers have also developed a safety management network, safety education and training guidelines, regular measurement of safety devices, and additional safety facilities. For the Chinese ship recycling yards' regulation and safety monitoring, the authors have recommended the application of

pre-cleaning for efficient environmental protection. In other words, before cutting, all hazardous substances and garbage on board are eliminated and securely processed in a green manner to achieve total breaking.

The purpose of the study by Zhou *et al*., 2021 [38] is to identify and evaluate the variables affecting workers' safety during ship recycling operations. Specific factors impacting safety were discovered by examining the primary procedures, hazardous chemicals, and potential dangers involved in ship recycling. 168 individuals from a range of positions within China's ship recycling sector—including academics, managers, and laborers—participated in a poll. Furthermore, a theoretical model containing hypotheses was created and evaluated through the use of structural equation modeling. With a focus on the significance of efficient dismantling operation management, the results show that a number of factors, including hazardous material disposal, the safety of dismantling operations, management of dismantling operations, equipment used in dismantling, and safety awareness, either directly or indirectly affect personal safety during ship dismantling. Changjiang Ship-Breaking Yard strictly adheres to plans and procedures for ship recycling, especially when handling hazardous materials, as was noted during a field study there. With this strategy, conservation of the environment and worker safety are guaranteed, and green ship recycling methods are encouraged in China.

A management and policy-oriented framework study was conducted by Ozturkoglu *et al*., 2019 [39] where the authors presented a preventive and sustainable risk management model for the ship recycling industry of Turkey. A triple bottom line approach has been demonstrated in this study using the fuzzy DEMATEL method to demonstrate and suggest managerial implications for long-term risk management in the ship recycling sector. The authors concluded and recommended that comparative studies can be carried out between diverse nations, particularly developing nations that face comparable hazards. Furthermore, risk can be increased using models other than TBL. Additionally, the provided methodology can be used in the study of different industries. In addition to displaying causal links and the important order, several MCDM approaches can also be utilized for sorting, categorization, and ranking.

Another article Mentes, 2023 [40] introduces a new framework for analyzing risks in both onboard and on-field operations at Aliağa Ship Recycling Facilities. It integrates various methodologies such as FMEA, OWGA, FVIKOR, and Resilience Engineering (RE) principles. While traditional methods like FMEA are effective in identifying failure modes and consequences, they may overlook the dynamic and interconnected nature of risks, particularly in complex systems where human and organizational factors are crucial. To address this, the article proposes a proactive risk analysis approach that combines the strengths of classical methods with RE principles. By doing so, it aims to enhance safety and reliability standards in the ship recycling industry through innovative and proactive measures.

5.2.4. Lack of Proper Training

Training facilities and scopes are low in shipbreaking countries. Even the authorities sometimes turn a blind eye in this regard, which seriously jeopardizes the issue of workers' safety. For sustainable implementation, a long-term training strategy and stable funding system are essential, along with awareness-raising campaigns and cooperation with local decision-makers to ensure compliance with international standards. Gunbeyaz *et al*. 2019 [41] noted that the SENSREC project, aligned with the IMO's Hong Kong Convention and ILO requirements, developed comprehensive training modules covering ship recycling administration, hazard awareness, environmental awareness, handling hazardous materials, and vocational education. Despite pilot training showing the need for significant improvement in current training practices, the IMO's second phase of the SENSREC project aims to support capacity-building and enhance worker training in Bangladesh.

The survey among workers in the study of Arslan *et al*., 2013 [33] revealed that ship dismantling workers provide a highly good reaction to more recent delivery methods, including computer-assisted learning, e-learning, and blended learning. These methods can be more explicitly explored to improve training facilities for these workers. In the same survey, respondents evaluated asbestos and hazardous training courses as not very successful, but they also rated firefighting, cutting and welding, and heavy machine operator training courses as quite effective.

5.2.5. Environmental Contamination

While not directly a health issue for the workers themselves, the practices in ship recycling yards can lead to environmental contamination. Pollutants like oil, heavy metals, and chemicals can spread to surrounding areas, impacting workers' families, nearby communities, and ecosystems. Memon and Zarar, 2016 [42] conducted a study on the shipbreaking industry of Pakistan through a case study of the Gadani and Balochistan regions where the conditions and implications of the industrial practices on the workers' community were elaborated. The research work has

attempted to outline the challenges and produce a thorough understanding of the shipbreaking industrial area, as well as the surrounding environment and working conditions of the nearby towns and workers. Hazardous waste management facilities are absent, and toxic items are not stored separately but rather discarded nearby at the expense of the environment, workers' health, and community safety. As a result, the number of health risks is increasing daily, and the victims are 12,000–15,000 workers and a 25,000-person community living in dangerous conditions close to the ship-breaking industry region. The location of the Gaddani Ship Breaking Industrial Area does not meet international environmental and social standards, despite some improvements being seen at yards, such as greater service of automatic equipment, including cranes and wheel loaders. The federal and provincial governments' players do not hold themselves accountable for any changes or investments made in the shipbreaking sector or the area around it. The study of Qayum and Zhu, 2018 [32] revealed the negative impacts of hazardous substances such as POPs, asbestos, and all toxins like PCBs, TBTs, heavy oils, PAHs, PVCs, etc., on the surrounding marine environment. Another study conducted by Khan *et al*., 2024 [43] highlights rising levels of persistent organic pollutants (POPs) linked to shipbreaking activities in Pakistan. Through a case study, the authors have examined the air quality through concentrations of pollutants around one shipbreaking facility in the Gadani region and found a hefty amount of the availability of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and short-chain chlorinated paraffins (SCCPs). Although there were limitations regarding the sampling methods and over-interpretation of results, the study used passive air samples to monitor the air pollutants, which revealed significantly higher concentrations of pollutants at ship-breaking yards compared to other locations.

Some shipbreaking yards in China and Turkey have taken steps to convert their facilities into green recycling ones. The study Neşer *et al*., 2008 [44] examines whether recent improvements in yard procedures and Environmental laws in Turkey are adequate to designate Aliağa as capable of "green recycling," enabling ship owners to recycle vessels in an environmentally responsible manner. Despite the increasing demand for shipbreaking due to the expanding global fleet, responsible recycling capacity remains limited, but Aliağa has taken important initial steps in this direction. In order to address the levels of oil contamination across the coastline in the Aliağa ship recycling zone, two additional studies were carried out from the perspective of Turkey for heavy metal contamination and polycyclic aliphatic and aromatic hydrocarbon contamination across the Aliaga coast of Turkey. Neser *et al*., 2012 [45] conducted both of these as a part of a project, the DIVEST (Dismantling of Vessels in Enhanced Safety and Technology), a research and technology development collaborative project funded by the European Union. In both these studies, the sediment concentrations of heavy metals and PAHs were illustrated via the results accumulated.

Neser *et al*., 2012 [45], in 2009, found C17 as the main species, whereas in 2010, C18 became the dominant species. Overall, the area was found to be extremely contaminated based on PAH levels in the sediments from Aliaga. Diagnostic ratios of aliphatic hydrocarbons revealed that the contamination in the sediments, resulting from ship dismantling activities, was primarily of petroleum origin. PAH indices indicated that pyrolitic sources were the main contributors to PAHs in the sediments. The TEL/PEL analysis suggested the likely presence of acutely hazardous PAH chemicals in the Aliaga sediments. The study concluded that the highest concentrations of aliphatic hydrocarbons and PAHs were influenced by shipping activity, the shipbreaking industry, steel works (including iron smelters and roller mills), and petrochemical complexes. Eronat *et al*., 2019 [46] utilized satellite monitoring to assess oil pollution in Çandarlı Bay, Turkey, a ship recycling zone, over 210 sampling days from 2015 to 2017. The study found that oil spill coverage increased from 16.4% in 2015 to 24.2% in 2017, with recurring leaks at the same location. The research highlighted that satellite monitoring is crucial for effective oil spill detection and analysis and recommended the development of a satellite-based monitoring system to address regional oil transportation trends and improve spill management.

Besides the articles outlined above, two other papers have been found to portray significant information on occupational safety and health factors for ship recycling. The paper of Yan *et al*., 2018 [47] presents an overview of the shipbreaking industry in China and globally, focusing on hazardous materials used in shipbreaking and their impact on the environment and human health. It then explores the concept of green shipbreaking technology, particularly the use of abrasive water jet cutting. The feasibility of implementing this technology is studied, considering its impact on environmental protection, safety, efficiency, and cost-effectiveness. Another survey-based article has been published, which contains essential findings on the highest risk-prone element of the operational ship recycling process carried out in Bangladesh. Mehtaj *et al*., 2024 [48] investigated the occupational hazards in Bangladesh's ship recycling industry and proposed strategies to enhance safety standards. This

Table 1: Research Papers Focusing on Occupational Safety and Health Associated with Ship Recycling and Shipbreaking in India in Chronological Order

Authors	Paper Title with Year of Publishing	No. of citations	Key Research Findings
P. C. Deshpande, A. K. Tilwankar, S. R. Asolekar [16]	A novel approach to estimating potential maximum heavy metal exposure to ship recycling yard workers in Alang, India, 2012, *Science of The Total Environment Journal*	76	• Cumulative maximum heavy metal concentrations estimated between 113 g/Nm3 and 428 g/Nm3 at varying wind speeds. • Lead (Pb) content in outside air is estimated between 8 and 30 g/Nm3, surpassing Indian National Ambient Air Quality Standards (NAAQS).
P. C. Deshpande, P. P. Kalbar, A. K. Tilwankar, S. R. Asolekar [47]	A novel approach to estimating resource consumption rates and emission factors for ship recycling yards in Alang, India, 2013, *Journal of Cleaner Production*	43	• A new time-motion study technique has been developed to measure the inputs (fuel, labor, oxygen) and outputs (emissions, paint, and steel deposits on sediment) of the plate-cutting process in ship recycling. • Introduction of a novel plate-cutting parameter as a functional unit for the study. • Input study reveals 6.2 kg of fuel used per kilometer of plate cut per millimeter of plate thickness. • Output results show CO2 emissions estimated at 21.77 kg per km of plate cut length per mm of plate thickness, with paint emissions to air and sediment deposition at 0.9 kg and 1.34 kg per km of plate cut per mm, respectively.
A.M. Hiremath, A.K. Tilwanker, S.R. Asolekar [3]	Significant Steps in Ship Recycling Vis-A-Vis Wastes Generated in A Cluster of Yards in Alang: A Case Study, 2014, Journal *of Cleaner Production*	100	• Comparison of emission factors (metric tons per ship and kg/LDT) of landfillable wastes, incinerable waste, and bilge water for different ship types recycled in Alang ship dismantling yards.
K. Garmer, H. Sjöström, A.M. Hiremath, A.K. Tilwanker, G. Kinigalakis, S. R. Asolekar [48]	Development and validation of a three-step risk assessment method for ship recycling sector, 2015, *Safety Science Journal*	43	• The research aims to find a safer and more efficient method for disposing of end-of-life ships to ensure India's comparative advantage over Bangladesh in the ship recycling industry. • The study proposes a three-step risk assessment approach, comprising a preparation of a safe ship recycling plan, identification of hazardous jobs, and deeper risk assessment with recommendations for risk minimization.
A.M. Hiremath, S.K. Pandey, S.R. Asolekar [49]	Development of ship-specific recycling plan to improve health safety and environment in ship recycling yards, 2016, Journal *of Cleaner Production*	78	• The study analyzed the entire recycling process of two bulk carriers, two general cargo ships, and two container ships, focusing on articulating a "ship-specific recycling plan." • Occupational and health safety hazardous situations were estimated using what-if-analyses, considering areas inside the ship, intertidal zone, and primary and secondary zones. • Main issues identified included workers' safety, occupational health hazards, risks of injuries or fatalities, working conditions, and the environmental impact of recycling.
R. Singh, B. Rao, R. Asolekar [13]	Treatment and Disposal of Glass-wool and Asbestos Bearing Waste-Insulation Materials from Ship Dismantling Yards in India, 2017, *15th International Conference on Environmental Science and Technology*	6	• The study evaluated the methods used in ship dismantling across Alang, India, particularly focusing on the management of asbestos and glass wool wastes. • Phthalates were identified as posing a significant threat to the marine ecosystem and were flagged as potential endocrine disruptors. • The study highlighted the presence of aromatic hydrocarbons, which can persist in the environment and pose risks to both human health and the ecosystem
R. Singh, J.W. Cherrie, B. Rao, S. R. Asolekar [14]	Assessment of the future mesothelioma disease burden from past exposure to asbestos in ship recycling yards in India, 2020, *International Journal of Hygiene and Environmental Health*	27	• The study underscores the high mortality and cancer rates among workers exposed to asbestos during shipbreaking activities • Employees working in the areas near boiler rooms, engine rooms, and other asbestos-containing environments are identified as particularly vulnerable to asbestos exposure and associated health risks. • It highlights the urgent need for evidence-based studies to develop effective policies and programs for worker protection

investigation is based on on-ground surveys across 18 ship recycling facilities in Bangladesh. The research assessed the risk patterns present in the ship recycling sector, with particular attention to highly dangerous tasks related to (i) explosion risks during primary cutting operations at the intertidal zone, (ii) falling hazards during outer anchorage inspections, and (iii) falling and crushing hazards during block cutting and heavy object handling. The list of potential hazards was identified in the range of low, medium, high, and undefined variables, along with categorization. The study evaluated risk patterns via a risk matrix indicating the least to highest risk zones through color codes in levels 1 to 5. A list of toxic substances produced as a

Table 2: Research Papers Focusing on Occupational Safety and Health Associated with Ship Recycling and Ship Breaking in Bangladesh in Chronological Order

Authors	Paper Title	No. of citations	Key Research Findings
N.M.G. Zakaria, M.T. Ali, Kh. A. Hossain [26]	Underlying Problems of Ship Recycling Industries in Bangladesh and Way Forward, 2012, *Journal of Naval Architecture and Marine Engineering*	51	• Non-compliance with safety regulations during cutting operations leads to various accidents. • Issues such as improper plate cutting sequence, neglect of standardized techniques, and carrying heavy plates without safety measures pose threats to workers. • Accidents include falling from heights, falling heavy objects, and incidents in confined spaces due to inadequate ventilation. • Fire explosions, particularly in oil tankers, are a significant cause of fatal accidents in Bangladeshi ship recycling yards.
R.K. Saha, M.S. Islam, M.M. Rahman [32]	Safety Management for Bangladeshi Ship Breaking Industries Perspective, 2013, *Global Journal of Researches in Engineering*	9	• The study highlighted that shipbreaking activity has resulted in severe accidents and injuries including the death of nearly 400 workers over a decade with no fulfillment or enforcement of strict safety and regulations. • The authors have emphasized safe zoning, and adherence to International safety standards and Govt. policies to ensure safe and efficient shipbreaking operations.
Kh. A. Hossain [30]	Overview of the Ship Recycling Industry of Bangladesh, 2015, *Journal of Environmental & Analytical Toxicology*	57	• Lack of proper safety equipment or personal protective equipment (PPE) leads to inhalation of toxic gases and eye injuries. • Environmental impacts include pollution of the sea, soil, and groundwater due to unsafe management of hazardous wastes. • Hazardous substances such as heavy metals, asbestos, TBTs from paints, PCBs, etc., contribute to environmental pollution. • Environmental impacts include pollution of the sea, soil, and groundwater due to unsafe management of hazardous wastes.
S.M.M. Rahman, R. M. Handler, A. L. Mayer [50]	Life cycle assessment of steel in the ship recycling industry in Bangladesh, 2016, *Journal of Cleaner Production*	94	• Rebar made from recycled scraps saves 16.5 GJ of energy and reduces CO2eq emissions by 1965 kg per ton compared to new rebar production. • Rebar production from recycled steel is ten times less harmful to human health than primary production from iron ore. • Changing cutting methods or using protective gear can significantly reduce local environmental and health impacts.
M.S. Hossain, A.N.M. Fakhruddin, M.A.Z. Chowdhury, S.H. Gan [17]	Impact of ship-Breaking activities on the coastal environment of Bangladesh and a Management System for its Sustainability, 2016, *Environmental Science & Policy Journal*	110	• Heavy metals associated with ship-breaking activities, such as lead, mercury, cadmium, iron, aluminum, zinc, copper, chromium, and manganese, have high concentrations in sediment and seawater. • Atmospheric pollutants like PAHs, PCBs, organotins, asbestos, and others have been identified within ship-breaking activity areas, causing cell damage, mutations, immune system harm, cancerous diseases, neurological damage, and other illnesses over prolonged exposure periods.
S. Rahman [18]	Aspects and Impacts of Ship Recycling in Bangladesh, 2017, *Procedia Engineering Journal*	33	• Hazardous materials from ship recycling activities in Bangladesh such as PCBs, PVCs, PAHs, TBTs, oil, asbestos, heavy metals, isocyanates, and radioactive particles threaten human lives and the environment. • Heavy metals like cadmium, copper, mercury, zinc, and lead, with lead having the highest exposure, pose detrimental effects on human health, especially to young children.
H. Rabbi, A. Rahman [4]	Ship Breaking and Recycling Industry of Bangladesh; Issues and Challenges, 2017, *Procedia Engineering Journal*	57	• Accidents within ship-breaking facilities have led to multiple deaths, including incidents such as explosions, falling from heights due to improper safety measures, and lack of Personal Protective Equipment (PPE) usage. • Workers are often deprived of their rights when victimized by accidents. • Minor accidents like brushing, broken bones while carrying heavy metals, and cuts from sharp edges inside ship-breaking yards are also reported.
M.S.H. Patwary, D. Bartlett [27]	Impacts Of Shipbreaking Industry in Bangladesh: Search for A Sustainable Solution, 2019, *European Journal of Engineering and Technology*	10	• Occupational health and safety issues within the ship recycling industry of Bangladesh include exposure to hazardous materials such as asbestos, heavy metals, batteries, PCBs, PVCs, and PAHs. • Frequent accidents reported in the industry include falling from heights, cuts, injuries, explosion-based injuries, and confined space entry accidents. • Mitigation measures for controlling these occupational health and safety issues are discussed by the authors.

(Table 2). Continued.

Authors	Paper Title	No. of citations	Key Research Findings
I. Alam, S. Barua, K. Ishii, S. Mizutani, M.M. Hossain, I.M.M. Rahman, H. Hasegawa [19]	Assessment of health risks associated with potentially toxic element contamination of soil by end-of-life ship dismantling in Bangladesh, 2019, *Environmental Science and Pollution Research Journal*	36	• The study found the order of soil metal concentrations to be Cd> Zn > Cr > Cu > Pb > Ni > Mn>As. • The storage zone of Bangladesh's Ship Breaking and Recycling Industry (SBRI) had the highest level of contamination, as determined by the Soil Pollution Load Index (SPLI). • The study estimated that the potential cancer risks due to As, Cd, Cr, Ni, and Pb were within safe limits.
S. A. Gunbeyaz, R. E. Kurt, R. Baumler [37]	A study on evaluating the status of current occupational training in the ship recycling industry in Bangladesh, 2019, WMU Journal of Maritime Affairs	36	• The SENSREC project developed comprehensive training modules aligned with the IMO's Hong Kong Convention and ILO requirements. • The second phase of the SENSREC project, conducted in 2018, supports capacity-building in Bangladesh using previously developed materials.
M. J. Rizvi, M.R. Islam, O. Adekola, O. N. Margaret [51]	A sustainable shipbreaking approach for a cleaner environment and better wellbeing, 2020, *Journal of Cleaner Production*	19	• Computer simulations indicate that improper management of toxic waste during beaching can result in its accumulation in the yard and seepage into the soil, leading to contamination of seawater and degradation of water quality. • Simulations suggest that constructing a bed with gradually increasing pebble sizes can help contain hazardous materials and mitigate environmental damage.
M. Tanha, G. Michelson, M. Chowdhury, P. Castka [31]	Shipbreaking in Bangladesh: Organizational responses, ethics, and varieties of employee safety, 2022, Journal of Safety Research	16	• Contrary to expectations of uniformly poor outcomes, the findings revealed varying workplace safety practices among the three shipbreaking firms. • Firms with better safety outcomes demonstrated higher managerial commitment to improving safety, PPE, and training, implemented external certification, and had stronger management processes regarding workplace safety.
M. M. Ali, M. S. Islam, A. R. M. T. Islam, M.S. Bhuyan, A.S. S. Ahmed, M.Z. Rahman, M.M. Rahman [20]	Toxic metal pollution and ecological risk assessment in water and sediment at ship breaking sites in the Bay of Bengal Coast, Bangladesh, 2022, *Marine Pollution Bulletin*	75	• Results indicated that concentrations of these metals exceeded recommended limits in both water and sediment samples. • Arsenic and Cadmium levels showed significant variation between seasons, while Chromium and Lead levels remained consistent. • The Metal Pollution Index (MPI) and Contamination Factor (CF) indicated critical water quality, with high cumulative metal concentrations. • The Geoaccumulation Index (Igeo) suggested moderate to strong pollution in the area and sediment samples exhibited moderate to high contamination levels based on the CF, except for Chromium. • The Pollution Load Index (PLI) indicated high pollution by heavy metals across all sampling sites within the shipbreaking region.
M. N. Islam, S. Ganguli, N. Saha, M. M. Huda, M. A. Hoque, C. Peng, J. C. Ng [21]	Uncovering the impact of mega-scale shipbreaking yards on soil and crop quality in Bangladesh: A spatiotemporal dynamics and associated health risks of metal/loid contamination, 2023, *Journal of Hazardous Materials*	3	• Results showed contaminants, such as Cd, As, Pb, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Sn, Sb, and Tl posed potential health risks to the population, with Cd, As, Mn, and Pb identified as threats through rice consumption, and Pb, Cd, Tl, and Co through vegetable consumption. • The PCA-APCS-MLR model identified mixed anthropogenic and geogenic sources as prime contributors to soil contamination (69%), with industrial discharge from nearby ship recycling industries contributing about 24%.
A.B. Hasan, A.H.M. S. Reza, M. A. B. Siddique, M. A. Akbor, A. Nahar, M. Hasan, M. R. Uddin, M.N. Zaman, I. Islam [25]	Origin, Spatial Distribution, Sediment Contamination, Ecological and Health Risk Evaluation of Trace Metals in Sediments of Ship Breaking Area of Bangladesh, 2023, *Journal of Hazardous Materials*	17	• The study revealed that sediments from the ship-breaking location of Sitakunda, Bangladesh, included significant quantities of trace metals (Pb, Cd, Cr, Zn, As, etc.), with the majority of samples being categorized as extremely contaminated. • The risks associated with exposure to metals such as As, Cr, and Ni were found to be higher than acceptable. Hazard Quotients (HQ) were used to quantify non-carcinogenic health hazards, and the results indicated that the working community and their families were more likely to develop malignant diseases over time. • Principal component analysis and cluster analysis showed that shipbreaking-related anthropogenic sources are the main source of trace metals. In order to reduce the continuous health concerns posed by contaminated sediments, constant monitoring and management are required.

(Table 2). Continued.

Authors	Paper Title	No. of citations	Key Research Findings
N. Mehtaj, N.M.G. Zakaria, Z.I. Awal, S.S. Dipto, M.A.Hannan, A.K. Dev, M.T. Ali [44]	Ship Recycling Process in Bangladesh and A Survey-Based Risk Assessment with Mitigation Proposal, 2024, *Heliyon Journal*	10	• Based on careful field assessments of recycling yard operations in Bangladesh, this study offers a thorough representation of the process flow in the ship recycling sector. • By gathering data from 1074 workers and conducting a field survey across 18 ship recycling yards, the industry's inherent risk patterns are revealed, and cost-effective suggestions for reducing risks in high-risk settings are developed. • The study found that most high-risk zone involves activities such as primary cutting operations at the intertidal zone which often leads to fire hazards, inspection at outer anchorage by team members, workers falling from height during block cutting, and workers being trapped and crushed under heavy objects, and failure of mooring components while towing heavy block. • Regarding the high-risk areas identified by the study, the authors suggested practical steps and research-based solutions that the industry should use to promote progress in creating a ship recycling procedure that is safer and more environmentally friendly.
S. Hosen, O. Alam, M. Al Amin, M.S. Arif, C. Das, N. Sultana [45]	Impact of shipbreaking industries on the Sitakunda coastal environment, Chattogram by analyzing water quality parameters, 2025, *Marine Pollution Bulletin*	4	• A questionnaire survey based research was carried out among shipbreaking workers considering simple random sampling and purposive simple random sampling of water samples collected from shipbreaking yards • The tested water parameters were as turbidity (276–640 JTU), pH (6.3–6.7) and EC (1850–3636 µs/cm), while TSS (1925–4005), TDS (921–2150), chloride (543–1023), ferrous (1.4–34), DO (5.3–6.5), BOD (4.3–7.3), oil (30–7375), NH_3 (0.75–2.27), lead (55–107), copper (29–58), cadmium (0.2–0.7), mercury (0.01–0.12), zinc (71–128), chromium (18–107) and arsenic (0.02–5.3) in mg/l unit. • Researchers recommended regular monitoring by the domestic regulatory bodies for mitigating water pollution and preserving surrounding ecosystem.
T.R. Choudhury, M. Moniruzzaman, T.A. Anonna, H. Al-Asad, P. Samanta, F. Islam [46]	Evaluation of heavy metal contamination in soil, water, and fish in an industrial zone in Bangladesh: Ecological and potential health risk, 2025, *Regional Studies in Marine Science Journal*	9	• Researchers collected 5 seawater samples, 7 groundwater samples, 5 sediment samples, and 5 fish samples from shibreaking sites in Chattogram, Bangladesh • Water, sediment and fish samples were analyzed for As, Cr, Cu, Ni, Pb, and Zn; and heavy metal pollution index (HPI), entropy-weighted water quality index (EWQI), geo-accumulation index (Igeo), contamination factor (CF), enrichment factor (EF), metal pollution index (MPI), degree of contamination (Cdeg), pollution load index (PLI) and metal contamination index (MCI), hazard index (HI), lifetime carcinogenic risk (LCR) and health risk index (HRI) were also calculated. • All the groundwater and surface water samples exceed the WHO 2011 permissible limit. The metal distribution in sediment samples showed the order Zn > Ni > Cr > Cu > Pb > As. • EWQI and HPI values indicated that both groundwater and surface water quality were very poor, critically contaminated, and unsuitable for drinking purpose. The Igeo, CF and EF value in sediment samples showed the order As > Pb > Zn > Ni > Cu > Cr. • The Cdeg, PLI, and MCI index values indicated that certain shipbreaking sites (zonewise areas in Chattogram) are highly polluted.

result of ship-breaking activity was outlined which included asbestos, POPs, and heavy metals. The long-term and short-term risk evaluation issues were discussed and explained graphically. Based on the risk evaluation considering both long-term and short-term issues, a comparative analysis of very high-risk and high-risk activities across different stages of ship recycling was summarized, and another correlation of the survey outcome with 10 actual accident cases from within these 18 ship recycling facilities was also carried out. Finally, the authors provided a comprehensive risk mitigation proposal with regards to every involved ship cutting stage, and material handling and transfer using the heavy lifting equipment, to promote safe, and environment-friendly ship recycling in alignment with the Hong Kong Convention guidelines. The following section provides a chronological overview of the key research outputs derived from all the reviewed scientific articles from the respective five ship recycling states.

Besides, Hosen *et al.*, 2025 [49] analyzed the environmental impacts on the coastal environment of Sitakunda, Chattogram, Bangladesh shipbreaking zone based on assessment of the water quality. The study evaluated findings which indictaed potential contamination of local water quality by shipbreaking activities. Statistical analysis showed big F-value with

Table 3: Research Papers Focusing on Occupational Safety and Health Associated with Ship Recycling and Shipbreaking in Pakistan in Chronological Order

Authors	Paper Title	No. of citations	Key Research Findings
R. Ahmed, K. Siddiqui [33]	Ship Breaking Industry in Pakistan – Problems and Prospects, 2013, *International Journal of Management, IT and Engineering*	18	• Discussions mainly revolved around investment opportunities and profitability prospects within the industry. • Limited attention was given to health and safety regulations, with the paper mentioning that these regulations are not very strict in the context of Pakistan.
A.A. Memon, M. Zarar [38]	Comprehensive Analysis of Existing Infrastructure Conditions Correlating Ship-Breaking Activities and its Implications on Workers and Community A Case Study of Gaddani Town and Ship-Breaking Industry, Baluchistan, Pakistan, 2016, *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*	13	• The study outlined challenges faced by the shipbreaking industrial area, surrounding environment, and working conditions of nearby towns and workers. • The study estimated that 12,000–15,000 workers and a 25,000-person community are exposed to dangerous conditions near the shipbreaking industry. • Despite some improvements in yards, such as increased use of automatic equipment, workplace accidents remain a constant risk, often attributed to poor safety conditions.
S. Qayum, W. Zhu [28]	Ship Breaking Industry of Pakistan and its environmental effect on marine life and humans, 2018, *Indian Journal of Geo-Marine Sciences*	6	• The study highlighted the negative impacts of the shipbreaking industry in Pakistan on both marine life and human health, focusing on the presence of persistent organic pollutants (POPs), asbestos, and various toxins such as PCBs, TBTs, heavy oils, PAHs, and PVCs. • Legal regulations from the Basel and Hong Kong Conventions were presented, with a comparative analysis to demonstrate the current position of other ship recycling nations, including China, India, and Bangladesh.
A. S. Khan, S. A. Khan, A. Abbasi, D. Hajjar, A. A. Makki, H. Almahasheer, A. R.A. Moursy, R. Jim´enez-Ball esta [39]	Characterization of persistent organic contaminants in the atmosphere of Gadani's ship breaking yards and its surrounding: Implications for sustainable ship recycling practices, 2024, *Environment International Journal*	0	• The article explains that shipbreaking operations in Pakistan are specifically responsible for the rising levels of legacy persistent organic pollutants (POPs) in the adjacent communities. • Significant quantities of short-chain chlorinated paraffins (SCCPs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) were found in the air near a shipbreaking yard in Gadani. • The majority of organic compounds displayed high positive correlations, suggesting shared contamination sources and two primary sources of pollution were found by the Principal Component Analysis: one was connected to shipbreaking operations, and the other to outside sources.

small p-value in all the area-based water parameters, indicating the fact that most of the sampling points in the Sitakunda shipbreaking sites crossed the domestic government approved threshold values and standards. The potential heavy-metal pollution in both groundwater and surface water, sediment, and fish of different land-use locations near the shipbreaking zones located in Chattagram, Bangladesh was investigated in another study by Choudhury *et al*., 2025 [50]. Results evaluated showed higher health risks for children only via the ingestion. Dermal and inhalation exposure pathways was not found to pose any adverse health effects for both adults and children but both groundwater and surface water sample HI and LCR values showed adverse health effects at most of the sites. However, the health risk index (HRI) value indicated no adverse health impacts on humans due to fish consumption.

6. RESEARCH GAPS

Based on the reviewed articles, research gaps have been categorized through a compare-and-contrast approach. For this study, 2 regions were chosen: the South-Asian belt and Turkey. Since India, Bangladesh, and Pakistan hold the majority of the ship recycling global tonnage, it was assumed that the most research would be available for these 3 countries in the field of ship recycling, which does match with the findings from the search string using the keywords of shipbreaking and ship recycling. But when simplified with additional keywords to address the main focus point for this study, which involved the area of occupational safety and human health, the scenario coincided with the narrative of Bangladesh, being not only the largest ship recycling nation but also being a forefront at the heart of publishing scientific articles in the field of ship recycling and occupational safety and health factors. Likewise, India, being an economic power in this region, also conducted quality research in this field through academic institutions and surveys, but Pakistan lacked the number of publications over the years despite being another large global ship recycler.

China, being a nation that only recycles state-owned ships, has significantly contributed to this

Table 4: Research Papers Focusing on Occupational Safety and Health Associated with Ship Recycling and Ship Breaking in China in Chronological Order

Authors	Paper Title	No. of citations	Key Research Findings
W. Wu, Y. Lin, H. Shiue, C. Li, P. Tsai, C. Yang, S. Liou, T. Wu [15]	Cancer Incidence of Taiwanese Shipbreaking Workers Who Have Been Potentially Exposed to Asbestos, 2014, Environmental Research Journal	44	• The study examines the cancer risks linked to asbestos exposure among Taiwanese shipbreaking workers and finds that there are higher standardized incidence ratios (SIRs) for a number of malignancies, especially mesothelioma, lung, and oral cavity cancers. • The analysis highlights notable variations in cancer incidence rates by classifying people according to their job titles and exposure levels. • The results highlight the continued health dangers in the shipbreaking sector and the need for better safety rules to protect workers, notwithstanding certain limitations, such as the lack of personal exposure data and possible underestimating of cancer cases.
Z. Du, H. Zhu, Q. Zhou, YD. Wong [10]	Challenges and solutions for ship recycling in China, 2017, *Journal of Ocean Engineering*	48	• Safety management networks, education, training guidelines, and regular safety device measurements are in place in Chinese ship recycling facilities. • Compliance with the Hong Kong Convention (HKC) and European Regulations has not yet been fully adopted by Chinese ship recyclers and the government. • Adherence to international regulations like HKC could enhance competitiveness and profitability for ship recycling facilities. • Stakeholder cooperation among shipowners, recyclers, and government agencies is crucial for establishing a sustainable ship recycling sector.
Z. Du, S. Zhang, Q. Zhou, KF. Yuen, YD. Wong [24]	Hazardous Materials Analysis and Disposal Procedures during Ship Recycling, 2018, *Resources, Conservation and Recycling*	63	• Safe procedures for disposing of hazardous materials from ship recycling yards were depicted through case studies conducted at Jiang Men Zhong Xin Shipbreaking & Steel Co., LTD, and Jiangyin Changjiang Ship-Breaking Yard. • Recommendations included full utilization of the Hong Kong Convention and European regulations, technological improvements, and changes in management methods to assure the ship recycling industry's sustained growth.
H. Yan, L. Wua, J. Yu [43]	The environmental impact analysis of hazardous materials and the development of green technology in the shipbreaking process, 2018, *Journal of Ocean Engineering*	31	•The paper explores the concept of abrasive water jet cutting as green ship-breaking technology • The feasibility of the technology is studied, considering its impact on environmental protection, safety, efficiency, and cost-effectiveness.
Q. Zhou, J. Liang, Z. Du H. Zhu, Y. Jiao [34]	A study on factors affecting workers' safety during ship recycling, 2021, *Journal of Ocean Engineering*	24	• In this study, a survey involving 168 participants from various roles in the ship recycling industry in China was conducted. • Results demonstrated that factors such as hazardous material disposal, safety and management of dismantling operations, equipment, and safety awareness in some way impact personal safety during ship dismantling. • Observations at Changjiang Ship-Breaking Yard showed strict adherence to plans and procedures for ship recycling.

Table 5: Research Papers Focusing on Occupational Safety and Health Associated with Ship Recycling and Ship Breaking in Turkey in Chronological Order

Authors	Paper Title	No. of citations	Key Research Findings
G. Neser, D. Ünsalan, N. Tekoˇgul, F. Stuer-Lauridsen [40]	The shipbreaking industry in Turkey: environmental, safety and health issues, 2008, *Journal of Cleaner Production*	125	• This study evaluates Ailaga's steps towards green ship recycling • Whether Aliağa claims "green recycling" capacity, enabling ship owners to responsibly scrap vessels, given the recent improvements to the yards' procedures and Turkish environmental legislation, has been discussed
G. Neser, A. Kontas, D. Ünsalan, E. Uluturhan, O. Altay, E. Darılmaz, F. Küçüksezgin, N. Tekogˇul, F. Yercan [22]	Heavy metals contamination levels at the Coast of Aliagˇa (Turkey) ship recycling zone, 2012, *Marine Pollution Bulletin*	128	• Aliaga's water samples were contaminated with Hg, Cd, Pb, Cr, Cu, Zn, Mn, and Ni where Hg, Pb, Cu, Zn, and Ni exceeded TEL and PEL values • Sediment samples were found to be contaminated with Pb, Cr, Cu, Zn, and Ni • Among these, the ship recycling industry is responsible for lead, mercury, and cadmium pollution according to the author.

(Table 5). Continued.

Authors	Paper Title	No. of citations	Key Research Findings
G. Neser, A. Kontas, D. Ünsalan, E. Uluturhan, O. Altay, E. Darılmaz, F. Küçüksezgin, N. Tekog˘ul, F. Yercan [41]	Polycyclic aromatic and aliphatic hydrocarbon pollution at the coast of Aliag˘a (Turkey) ship recycling zone, 2012, *Marine Pollution Bulletin*	79	•Hazardous PAH were found in the sediments of Aliaga Shipbreaking yard. •Highest aliphatic hydrocarbons and PAH concentrations depend on the shipbreaking industry among other
O. Arsalan, R. E. Kurt, S. Mckenna, Tuba Kececi [29]	Training Needs Analysis for The Turkish Ship Dismantling Industry, 2013, *International Conference on Ship Recycling SHIPREC2013*	1	• Low job satisfaction and concerns with occupational health and safety among workers were found • Computer-assisted learning, e-learning, and hybrid learning is more preferable to workers • Asbestos and hazardous material training courses are considered ineffective Firefighting, cutting and welding, and heavy machine operator training courses are conceived as successful
A. Yılmaz, B. Karacık, S D. Yakan, B. Henkelmann, K-W. Schramm, OS. Okay [23]	Organic and heavy metal pollution in shipbreaking yards, 2016, *Journal of Ocean Engineering*	40	• PAH, PCB, and OCPs were found in concentrations ranging from 585 to 25,000 mg/kg in dry-weight • Quantity of Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn also exceeds the recommended value.
A. H. Eronat, F. Bengil, G. Neser [42]	Shipping and ship recycling-related oil pollution detection in Çandarlı Bay (Turkey) using satellite monitoring, 2019, *Journal of Ocean Engineering*	31	• Between 2015 to 2017, oil pollution levels at the Canderli Bay around the ship recycling activity zone were assessed • The study found that satellite monitoring effectively detected oil spills, with the percentage dispersion of oil spill detection ranging from 7.6% to 10.5% in 2017. • The authors recommended that employing satellite monitoring is essential for future oil spill monitoring systems
Y. Ozturkoglu, Y. Kazancoglu, Y.D. Ozkan-Ozen [35]	A sustainable and preventative risk management model for the ship recycling industry, 2019, *Journal of Cleaner Production*	65	• Cutting operations during ship breaking may be responsible for pyrolytic sources of PAH compounds. • Sediments also showed significant toxic levels of Cu, Pb, and Zn. • The authors recommended strict PCB inventory management and carefully removing antifouling paints and electrical equipment containing these harmful metals.
A. Mentes [36]	Risk analysis of on-field and onboard activities and resilience investigation of Izmir Aliaga Ship Recycling Facilities, 2023, *Journal of Ocean Engineering*	9	• The study introduces an innovative risk analysis framework for Aliağa Ship Recycling Facilities, merging methodologies like FMEA, OWGA, FVIKOR, and Resilience Engineering principles. • A proactive risk analysis approach including the strengths of classical methods with RE principles is proposed.

field in terms of quality research through their case-study-oriented interventions, and this particular quantifiable metric seems to be quite different compared to the existing case study research carried out in South Asian ship recycling yards of India, Bangladesh, and Pakistan. Lastly, Turkey, being another global leader in ship dismantling, has produced good research through their several funded-project initiatives, and being an EU state has had outstanding infrastructural developments which can also be aligned with their research studies. Hence, it is evident that regionally, there are comparable and contrasting research gaps and limitations in the context of every individual country, which have been further segmented and illustrated in the following sections.

6.1. Comparative Analysis across the Regions

6.1.1. Research on Hazardous Materials

The review paper highlighted several shared themes, one of which pertains to the emission and disposal of hazardous materials. While some studies aimed at quantifying the level of hazardous materials across the region, some were focused on the disposal of such metals and pollutants to ensure health and safety. In India, Deshpande *et al*., 2012 [16] conducted a study on developing a technique to demonstrate the maximum heavy metal exposures for ship recycling yard workers at Alang (India). Another method to estimate resource consumption rates and emission factors of the same recycling yard was developed by Deshpande *et al*., 2013 [51]. In the Alang case study of

Table 6: Comparative Summary of Ship Recycling Practices, Occupational Hazards, Regulatory Compliance, Safety Measures and Research Gaps Across Major Recycling Nations

Country	Recycling practice	Principal occupational hazards	Regulatory compliance status	Safety measures in place	Key research gaps
Bangladesh	Beaching (intertidal landing), Chattogram; 50,000 direct and 100,000–200,000 indirect workers (Mehtaj *et al*., 2022) [2]	Explosion of residual gas and fumes in tanks; falls from height; cuts and fractures from manual handling; asbestos; carcinogens in soil and water; absent first aid and emergency response (Rabbi and Rahman, 2017) [4]	HKC ratified June 2023; 17 SoC-certified facilities	Emerging sustainable dismantling approaches and HAZMAT risk assessment; PPE, training and housekeeping still inconsistent	Short- and long-term health effects on workers and surrounding population; effectiveness of enforcement and measured compliance with Basel and Hong Kong Conventions
India	Beaching (intertidal landing), Alang	Heavy metal exposure, with Pb in ambient air exceeding NAAQS; asbestos-linked mesothelioma burden; glass wool and phthalates; plate-cutting emissions	115 facilities certified as green recycling yards with SoC from IACS members (Class NK, RINA, IRS)	Three-step risk assessment method (Garmer *et al*., 2015) [48]; ship-specific recycling plans (Hiremath *et al*., 2016) [49]	Comprehensive health impact assessment covering both short- and long-term effects on workers and adjacent communities
Pakistan	Beaching (intertidal landing), Gadani	Hazardous substances discharged to the marine environment; inadequate waste management, safety gear and yard infrastructure	Lenient occupational safety regulation; 2 SoC-certified facility; sector development constrained by economic conditions	Limited documented interventions	Largest evidence deficit of the five studies: HAZMAT effects on water, soil and air; risk analysis methods; evaluation of regulation against international standards; sustainable pathways
China	Alongside / pier-breaking (floating method); systematic reverse-shipbuilding sequence (Du *et al*., 2017) [10]	Asbestos exposure and elevated cancer incidence; hazardous material handling during dismantling	Most advanced transition to green ship recycling among the five nations reviewed	Controlled, quay-based dismantling reducing environmental and safety risk; yard-level safety standards documented through case studies	Effect of these advances on worker and community health outcomes; cross-country comparative studies of regulatory adherence
Turkey	Landing/ slipway method (non-tidal beaching), Aliağa; soil-based landing areas progressively replaced with concrete flooring since 2006 (Sakin, 2023) [11]	Heavy metals and hydrocarbons in yard sediments, with concentrations rising between 2012 and 2016 (Neşer *et al*., 2012; Yılmaz *et al*., 2016) [23, 40]	Alignment with EU-adjacent standards; infrastructure upgraded, though construction standards for flooring remain undisclosed	Worker training-needs assessment; preventative risk management models; on-field and onboard risk analyses	Identification of specific health risks such as respiratory disease and cancer; interdisciplinary approaches; causes of rising sediment metal concentrations

Hiremath *et al*., 2014 [3], the most probable locations where asbestos, asbestos-containing materials (ACMs), and glass wool typically were found on board were investigated. Garmer *et al*., 2015 [52] developed and validated a three-step risk assessment method and highlighted a risk matrix to indicate the probability and severity of the occurrence of certain risk levels involved with ship recycling in India. Singh *et al*., 2017 [17] conducted another study to evaluate the existing methods of managing asbestos and glass wool wastes in the ship dismantling yards.

Similarly, this topic of hazardous material was quite prevalent in the studies of Bangladesh as well. Hossain *et al*., 2016 [21] examined the concentration of heavy metals associated with shipbreaking including lead (Pb), mercury (Hg), cadmium (Cd), iron (Fe), aluminum (Al), zinc (Zn), copper (Cu), chromium (Cr) and manganese (Mn) in the ship-breaking area of Chattogram and found that all of them have high concentrations in the sediment as well as seawater. The study conducted by Alam *et al*., 2019 [23] revealed the potential cancer risks due to As, Cd, Cr, Ni, and Pb were within the safe limit, and cancer risk among the shipbreaking yard workers due to soil contamination was only 6 to 7 people in every 100,000. The study of Ali *et al*., 2022 [26] investigated the levels of four toxic metals (Arsenic, Chromium, Cadmium, and Lead) in water and sediments at the Sitakunda shipbreaking area in Bangladesh. Likewise, Hasan *et al*., 2023 [29],

carried out statistical analyses and Monte Carlo simulations to identify the fact that almost 2 out of every 100,000 individuals at the shipbreaking yards might develop cancer due to exposure to trace metals like Pb, Cd, and As, which is similar to the analysis of Alam *et al*., 2019 [23]. The differences among these studies may be their confinement of research to assess the contamination of trace metals or heavy metals and not exploring any other radioactive element that also, to some extent, is derived from EOL ships, particularly from containments of any last delivered dangerous cargo in the scrap ship's final cargo shipment. Also, traces of radioactive substances other than mercury, such as Radium (226 Ra) and Thorium (232, Th). Also, among all the published articles focusing on heavy metals under the HAZMATs segment, only two researches outlined the negative impacts of trace metals in the case of agricultural productivity and vegetation-associated long-term health risks.

In Pakistan, Qayum and Zhu, 2018 [32] investigated the negative impacts of POPs, asbestos, and all toxins like PCBs, TBTs, heavy oils, PAHs, PVCs, etc., on the health of workers and affiliated people. In one case study of China by Du *et al*., 2018 [28], the carcinogenic effects of asbestos, glass wool, and other organotin posing severe risks to human health were discussed, and the disposal of such HAZMATs in shipbreaking yards in China was also studied. Zhou *et al*., 2021 [38] conducted a field study at Changjiang Ship-Breaking Yard and observed that the yard strictly adheres to plans and procedures for ship recycling, particularly in handling hazardous materials. Neser *et al*., 2012 [26] analyzed heavy metal concentrations and Yılmaz *et al*., 2016 [27] analyzed concentrations of PAH Compounds in sediments from the Aliağa ship recycling zone, Turkey. Only one unique study to assess the quantitative negative impacts of asbestosis or mesothelioma buildup amongst Taiwanese shipbreaking workers was obtained in this review paper. But India, Bangladesh, Pakistan, and even Turkey have not yet produced similar types of quantifiable research studies to examine the long-term gradual negative health aspects of asbestos-exposed ship recycling workers, particularly that have affected the flame cutter workers with cancer or cancerous diseases over a 2-decade assessment like that of the study conducted by Wu *et al*., 2014 [19].

Over the years, China, Turkey, and South Asia have all received scholarly interest in hazardous compounds related to the ship recycling industry. Ship recycling facilities approved by a party are required to securely remove any hazardous materials from ships per "Regulation 20 - Safe and environmentally friendly handling of hazardous materials" of the Hong Kong Convention. Workers and recycling in-charges must be familiar with and make use of the Ship Recycling Plan and the Inventory of Hazardous Materials. The facilities must also guarantee that trained personnel identify, label, package, and remove hazardous materials from the inventory before cutting the ship. This includes materials such as asbestos, PCBs, CFCs, hazardous liquids, heavy metals, flammable paints, and other non-structural hazardous materials. The authority is also responsible for making sure that any hazardous materials and waste from recycled ships are handled in a safe and environmentally responsible manner. To handle materials more effectively, the locations for waste management and disposal must be determined. To protect workers, the environment, and human health, all waste generated during recycling must be kept apart from recyclable materials and transported to a facility approved for waste management. Only then can they be properly treated and disposed of. Therefore, before the Hong Kong Convention is put into effect, more research on hazardous materials (HAZMAT) management in countries other than China is necessary. There is a significant lack of study on waste management facilities in these nations, particularly the concept of downstream waste management, safe transportation of HAZMATs, and the mandatory implementation and use of a TSDF (Treatment, Storage, and Disposal Facility) along with engineered landfill and leachate management for the produced wastes within the Ship Recycling Industry. Moreover, future studies may focus on evaluating workers' awareness and attentiveness regarding such hazardous materials. Figure **4** highlights a notable gap in research on hazardous material handling and human factors in Pakistan. Bangladesh, on the other hand, is actively conducting commendable research on worker safety. In contrast, the overall health and safety conditions for workers in China and Turkey have significantly improved, resulting in a lower number of recent research activities in these regions.

6.1.2. Research on Human Factors

Another common research trend among the studies reviewed was human factors, such as the health risks of the workers and surrounding population and workers' privileges. In India, a study was conducted to assess mesothelioma disease associated with asbestos exposure, which anticipated 4,515 mesothelioma-related deaths over the period studied [18]. Zakaria *et al*., 2012 [30] conducted research regarding callousness about labor safety in the ship recycling yards of Bangladesh, and it revealed that around 49% of accidents in shipbreaking facilities of Bangladesh occur due to oil tanker fire explosions. Rabbi and Aevelina, 2017 [4] also reflected on the consequences of accidents occurring within the ship-breaking facilities, which mainly include serious

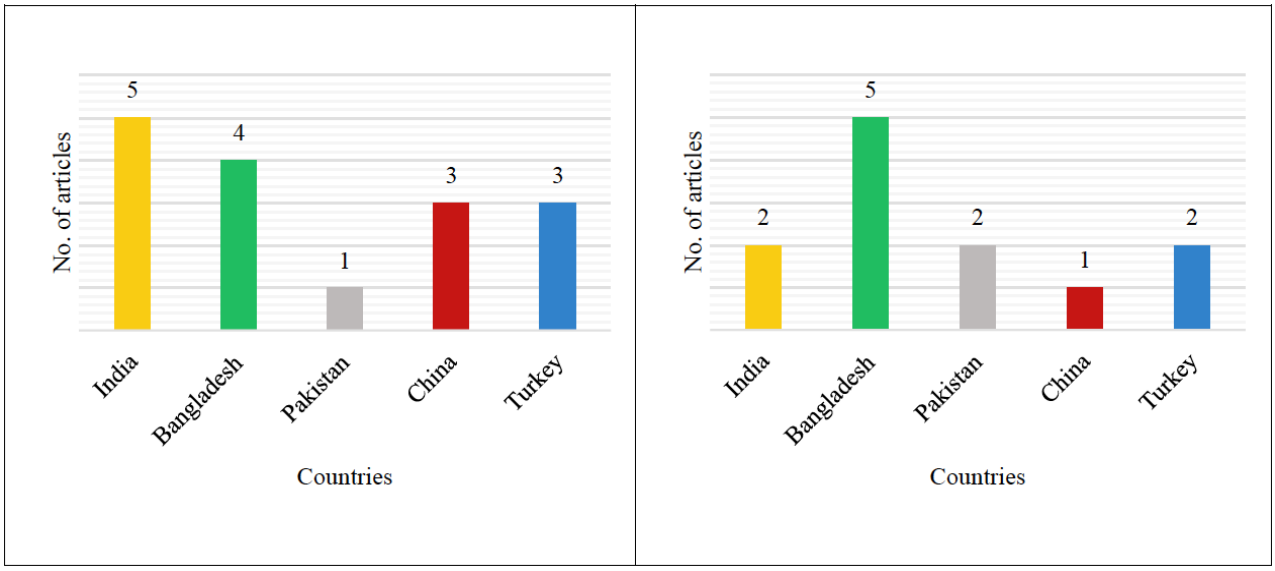

Figure 4: Distribution of the number of published articles on Health and Occupational Safety focusing on (i) HAZMAT (Left) and (ii) Human Factors (Right).

fire hazards due to improper gas freeing and gas monitoring procedures. Patwary *et al.*, 2019 [31] highlighted occupational health and safety lapse issues within the ship recycling industry of Bangladesh and probable steps for controlling these OHS issues. Tanha *et al.*, 2022 [35] investigated worker safety in ship recycling yards in Bangladesh by collecting data through interviews, site observations, and industry reports. Memon and Zarar, 2016 [42] carried out a case study on the shipbreaking industrial area of Pakistan and discussed the unsatisfactory condition of road infrastructure, waste management facilities, and utilities that directly affect the health and safety of the workers and associated people residing in the area. The investigation Wu *et al.*, 2014 [19] revealed an elevated number of incidences of cancer among male shipbreaking employees in Taiwan. China has made notable progress in terms of workers' safety. Du *et al.*, 2017 [13] observed that a safety management network, safety education and training guidelines, regular measurement of safety devices, and additional safety facilities have already been incorporated by ship recyclers in China. A survey among 168 respondents regarding factors influencing workers' safety in the ship recycling industry was performed, and it was found that disposal of hazardous material and equipment, management and safety of dismantling operations, and safety awareness explicitly and implicitly impact the personal safety of the workers [25]. Arslan *et al.*, 2013 [33] followed a thorough review of the training needs of Turkish ship dismantling employees and management and identified several key problem areas, such as low job satisfaction and concerns with occupational health and safety. Participants opined asbestos and hazardous material training as ineffective but found firefighting, cutting and welding, and heavy machinery operator training effective.

It is a general conception that the occupational safety of the workers in the ship recycling industry is not given as much importance as required, and hence, there were several studies regarding this issue. However, Regulation 22 – Worker Safety and Training of the Hong Kong Convention mandates that ship recycling authorities are required to prioritize worker safety via definite measures. First and foremost, they have to make sure that all ship recycling operations have access to, maintain, and employ personal safety equipment and clothes. In addition, they need to put in place training initiatives that equip their staff with the knowledge and abilities needed to carry out diverse ship recycling tasks in a safe manner. Above all, a thorough approach to worker safety is stressed by the need that all employees of the Ship Recycling Facility to complete the necessary training and familiarization before participating in any Ship Recycling activity. From the studies, it is apparent that the effectiveness of safety training among workers has yet to be investigated in Bangladesh and India. While in China, Pakistan, and Turkey, the case was investigated through surveys, further study is required to solve the problems associated with it. Additionally, more effective and comprehensive training methods should be employed in the countries of South Asia as recommended by various organizations [56, 57]. Please add full stop after [56, 57] Since explosions, falling from heights, toxic gas inhalation, etc. are some of the common forms of safety threats in this industry, scopes of implying machine learning for risk assessment and precaution activities can be explored. Mehtaj *et al.*, 2024 [48] conducted an extensive survey-based risk assessment study across 18 ship recycling yards in Bangladesh whereby through collective data on the probability and severity of the occurrence of some common issues like explosion

during cutting, falling from heights, and being hit or crushed by objects, the risk pattern could be understood. If data-driven approaches or trend analysis research can be carried out, then more substantial outcomes may be derived through ground data. A 2-decade accident analysis investigation may be carried out across South-Asian ship recycling facilities with the utilization of machine-learning or advanced computing tools to generate the trends, understand the existing pattern of hazards, and thus propose ideal, efficient, and safe mechanized techniques to minimize the hazards and elemental risks involved.

6.1.3. Critical Comparative Assessment: Best Practices, Persistent Challenges and Lessons

While the preceding comparison establishes what has been studied in each region, a critical understanding of the reviewed articles, reveals that the five ship recycling nations occupy distinctly different positions on the path towards safe and sustainable ship recycling, and that the determinants of their positions are as much infrastructural and institutional as they are technical.

The clearest divergence lies in the dismantling method itself, and it propagates through every subsequent safety outcome. China's alongside cutting or pier-breaking approach, in which vessels are disassembled in a controlled reversal of the shipbuilding sequence, permits containment of run-off, stable working platforms, and the use of fixed lifting equipment. Turkey's slipway landing method, reinforced by the progressive replacement of soil-based landing areas with concrete flooring, occupies an intermediate position: it retains the economic advantage of gravity-assisted vessel positioning while limiting direct discharge into the intertidal zone. The beaching method relied upon in Bangladesh, India and Pakistan offers the lowest capital requirement and the fastest throughput, but structurally precludes impermeable containment and obliges workers to operate on unstable, tidally inundated ground. The reviewed literature therefore suggests that method selection is not merely an operational preference but the principal upstream determinant of occupational risk exposure.

Against this backdrop, India represents the most instructive case of reform within the beaching paradigm. According to the report of PIB Delhi, the certification of 115 facilities against Statements of Compliance issued by IACS member societies demonstrates that yard-level upgrading, documented recycling planning and third-party verification can be achieved without abandoning intertidal landing altogether. The parallel development of structured risk assessment methodologies and ship-specific recycling plans indicates a research community working in close alignment with industrial practice. Turkey offers a complementary lesson from a different direction: its literature is distinguished by sustained attention to the worker as the unit of analysis, through training-needs assessment and preventative risk management modelling, rather than treating safety solely as a function of yard infrastructure.

Bangladesh occupies a position of rapid formal progress accompanied by a substantial implementation deficit. Ratification of the Hong Kong Convention in 2023 was decisive in bringing the instrument into force globally, yet the number of certified facilities remains small relative to the size of the workforce, estimated at 50,000 direct and up to 200,000 indirect participants. As per Business Standard news report, Bangladesh now has 17 HKC-compliant facilities while many facilities are under development. The recurrence in the reviewed studies of the same hazard categories over more than a decade — residual gas explosions during hot work, falls from height, and the absence of emergency response provision — suggests that regulatory adoption has outpaced the diffusion of basic safety practice at the working face.

Pakistan presents the most acute concern, and it is as much an evidentiary concern as a substantive one. Only four studies met the inclusion criteria for this review, against sixteen for Bangladesh and eight for Turkey. The consequence is that conditions at Gadani cannot presently be characterised with the confidence available elsewhere. There are currently 2 HKC-compliant facilities in Pakistan as per Tradewinds report, and the absence of a substantial number of SoC-certified facility means that neither internal reform nor external verification is generating the documentation that research would otherwise draw upon. Evidentiary scarcity should not be mistaken for the absence of hazards.

Three lessons emerge with reasonable clarity from this comparison. First, compliance certification functions as a diffusion mechanism rather than merely a gatekeeping one: the Indian experience indicates that once a critical mass of yards pursues certification, documented procedure becomes a competitive expectation rather than a regulatory imposition. Second, infrastructural investment and human-factors intervention are complements rather than substitutes; Turkey's training-oriented literature and China's containment-oriented practice each address a failure mode the other does not. Third, the research effort itself is unevenly distributed in a manner that correlates with, and plausibly reinforces, the gradient in safety performance — the jurisdictions with the weakest documented conditions are also those least studied.

Redressing this imbalance is a precondition for the comparative policy learning that sustainable maritime recycling requires.

6.2. Chronological Analysis within the Regions

6.2.1. India

Seven research studies on ship recycling from the perspective of health and safety were found within the timeline of 2008 to 2024 and reviewed. A pattern of progress can be detected in the research focus and methodologies employed over time. Initially, the focus was on estimating heavy metal exposure and resource consumption rates in ship recycling yards in Alang, India. Further studies were conducted on the practical aspects, including waste generation, recycling plans, and most importantly, risk assessment methods. There is a particular emphasis on addressing hazardous materials from ship dismantling yards, indicating a growing concern for worker health and safety. The progression climaxes into assessing the future disease burden associated with past asbestos exposure, suggesting a shift towards broader public health implications and long-term consequences of ship recycling activities. Overall, the progression reflects an evolution from initial assessments and practical solutions for improving operational efficiency and safety to more comprehensive evaluations of health and safety impacts associated with ship recycling practices. However, a comprehensive health impact assessment that considers both short-term and long-term health effects on workers and the associated community due to ship recycling activities can be regarded for further study.

6.2.2. Bangladesh

A total of sixteen Bangladeshi papers were reviewed in the context of occupational health and safety for this study. The initial papers focused on an overview of the study, including underlying problems and challenges associated with it. Further researches were conducted on the effects of various hazardous materials on the health and safety of workers and the quantity of carcinogenic materials in the water and soil was also investigated. Additionally, studies explore employee safety concerns and organizational responses to ensure worker well-being. More recent research focuses on proposing sustainable approaches for shipbreaking and risk assessments of hazardous material. Nonetheless, more studies should be conducted on the short and long-term health effects of this industry on the workers and associated population. More research is required to evaluate the effectiveness of existing regulations and enforcement mechanisms in ensuring compliance with safety standards in ship recycling yards, and the level of compliance with existing regulations, such as the Basel Convention and Hong Kong Convention, can be assessed.

6.2.3. Pakistan

Despite Pakistan's success in the shipbreaking industry, there is an inadequacy of literature focusing on health and safety perspectives in this region. Only four studies met the criteria for inclusion in this review paper. The earliest study briefly discussed Pakistan's lenient occupational safety regulations in the shipbreaking industry. Another study examined the safety and standard of living of ship recycling yard workers, including waste management facilities, safety gear, safety facilities, and surrounding infrastructure. A third study primarily addressed hazardous substances and their impact on the marine environment. Further research on hazardous materials and the occupational health and safety of workers and the surrounding population is required in Pakistan. Studies investigating the effects of hazardous materials on surrounding environments such as water, soil, and air, as well as risk analysis methods, are warranted. Additionally, there is a need to evaluate existing regulations and compliance with international safety standards. Sustainable approaches for the future of shipbreaking and the industry's impact on the health of workers and other associated individuals should also be explored.

6.2.4. China

China has made significant progress in transitioning towards green ship recycling compared to other countries investigated in this study. The five research articles identified in this review illustrate the evolving landscape of the ship recycling industry in China. Initial investigations focused on identifying industry challenges and managing hazardous materials during the recycling processes. Subsequent studies delved into the environmental impact of these materials and the safety of the workers involved. Case studies provided insights into the operational conditions and safety standards across different ship recycling yards in China. While commendable progress has been made in the Chinese ship recycling sector, further research is needed to assess the effect of advancements in worker and community health and safety standards. Comparative studies across countries can also shed light on the importance of adhering to safety regulations in achieving sustainable ship recycling practices.

6.2.5. Turkey

According to the eight studies considered for the review, the health and safety perspectives of shipbreaking workers have progressed significantly over the years in Turkey. Initially, studies focused on identifying environmental, safety, and health issues

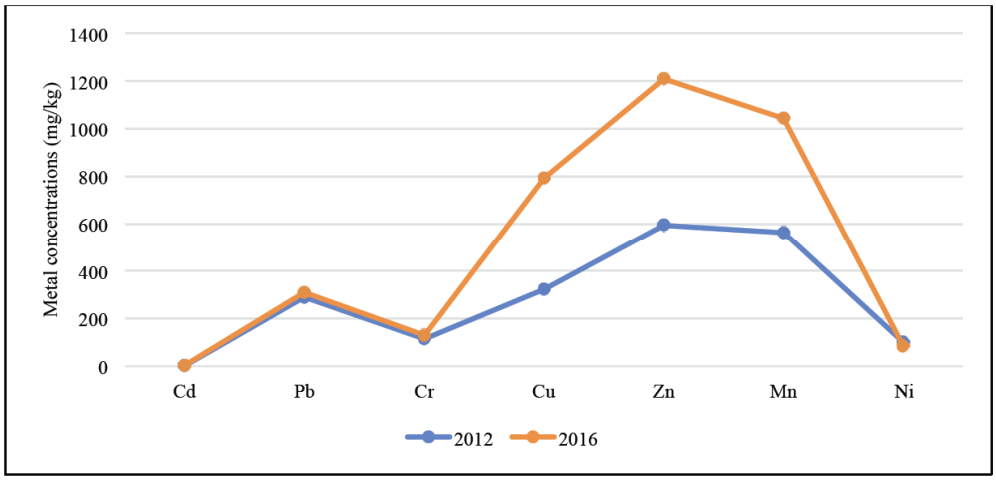

Figure 5: Hazardous metal concentration in the sediments of Aliaga Shipbreaking yard.

within the shipbreaking industry. Subsequent research inspected specific pollutants found in ship recycling zones, such as heavy metals and hydrocarbons. From the studies by Neser *et al*., 2012 and Yılmaz *et al*., 2016 [26, 27], the changes in metal concentrations around the Aliaga shipbreaking yard (Figure **5**) in Turkey can be observed, which opens the door to future studies on the reasons behind the increment of certain metals over only four years.

Moreover, there were efforts to assess the training needs of workers in the ship recycling industry and to develop preventative risk management models for the industry. Recent research has also aimed at conducting risk analyses of on-field and onboard activities in ship recycling facilities. Although the former studies cover many broad aspects, some studies are required to identify specific health risks (such as respiratory disease, cancer, etc.) and an interdisciplinary research approach might bring out better results.

This review has identified several significant research gaps that warrant further investigation.

- Firstly, there is a critical need for more extensive research on the long-term health effects of exposure to hazardous materials commonly encountered in ship recycling, such as asbestos, heavy metals, and persistent organic pollutants. Understanding these impacts is essential for developing effective health and safety protocols. Conducting longitudinal epidemiological studies tracking the health outcomes of workers over several decades to establish a clear causal link between exposure and specific health conditions in all regions is very significant in this regard.

- Secondly, there is a need for comprehensive studies on the effectiveness of various interventions aimed at reducing occupational safety and health (OSH) risks in the ship recycling industry. This includes evaluating the success of current safety measures and identifying innovative approaches that could better protect workers. One direction for research in this area is to implement and evaluate pilot safety programs that incorporate advanced safety equipment, enhanced personal protective gear, and improved emergency response protocols, and then measure the reduction in accident rates and health issues before and after the implementation of these interventions.

- Thirdly, the effectiveness of existing training methods for ship recycling workers needs a thorough evaluation. This includes not only general training programs but also the development of region-specific training initiatives that address the unique challenges faced by workers in different geographic locations.

- Research is needed to assess the economic and social impacts of ship recycling on local communities and economies. Understanding these impacts can help policymakers create more balanced and beneficial regulatory frameworks.

- Finally, there is a pressing need for research focused on developing sustainable ship recycling practices that minimize environmental harm while maximizing economic and social benefits. This includes exploring new technologies and methods that could make the industry more sustainable in the long term.

7. LIMITATIONS

This study has been conducted to provide an inclusive overview of the ever-dynamic global ship

recycling industry and its deep-rooted affiliation with occupational safety and health factors, which has been a key concern for global organizations, flag states, ship owners, recycling states, concerned technical and safety professionals, and environmentalists. With the Hong Kong Convention already enforced on 26th June 2025, there will be so much to work on for the global community and recyclers to address the prevalent occupational safety and health-wise issues, and the achievement of international compliance standards for ship recyclers, mostly focusing on providing a safe, robust, and mechanized working platform to protect and safeguard the workforce, and environment through continued quality management, safety at work practices, PPEs and training and housekeeping and Govt. monitoring. Thus, this review study was carried out to focus on the existing impending issues, through which global researchers can suggest novel and industry-specific ideas as pathways for improving and bettering the Ship Recycling practices particularly across South Asia as more and more ships will require dismantling in the coming 20 years with the rise in global shipping fleet. However, while carrying out this review study, the authors have faced some limitations with regard to accessibility in reviewing research articles across many other platforms that are not available in Bangladesh, where this article has been developed. Also, the ship recycling industry and its occupational health and safety considerations have been reviewed only for 5 destinations, principally, the global ship recycling leaders – India, Bangladesh, Pakistan, and Turkey, and South Asian regional recycler China. This review study has not shed light on the research conducted across EU-region countries, North American ship scrap yards, or other newly developed recycling destinations like Egypt, South Africa, and Vietnam.

7.1. Future Research Directions and Emerging Innovations in Sustainable Ship Recycling

The research gaps identified in the preceding section are unlikely to be closed through incremental refinement of existing manual practice alone. A distinct body of work has begun to emerge in which robotics, sensing, and data-driven decision support are applied to end-of-life vessel dismantling, and this section examines those developments and the research agenda they imply. A structural observation should be made at the outset: while artificial intelligence and machine learning have been extensively investigated across shipping operations, with systematic reviews covering energy saving, carbon mitigation and intelligent ship development over the period 2019 to 2025, the recycling phase of the vessel lifecycle has received disproportionately little attention.

7.2. Robotics and Semi-Automation of Dismantling Operations

The most substantial initiative in this domain is the SHEREC project [58], funded under the European Union's Horizon Europe programme. Coordinated by HKTM and bringing together sixteen partners from ten European countries — universities, companies, research institutes and a non-governmental organisation — the project seeks to improve occupational health and safety in ship recycling by integrating robotics, data and artificial intelligence, while also guarding against environmental contamination by hazardous substances. Its programme comprises three elements: semi-automation of the preparation phase using an AI-powered drone that inspects the ship's interior to locate hazardous materials; generation of an automated recycling plan using a digital twin of the vessel together with AI-based planning methods; and automation of cutting and paint removal through two mobile robotic systems capable of autonomous or tele-operated working.

The occupational significance of this architecture lies in its sequencing. By relocating hazardous material identification from human survey to autonomous inspection, and cutting from manual torch work to tele-operated robotics, the approach removes the worker from the two operations that the studies reviewed in Section 5 associate most consistently with fatality and chronic exposure. Development work on the aerial platform has centred on a drone equipped with visual and chemical sensors together with specialised tools for the detection and precise localisation of hazardous materials within vessels, and the engineering challenge has been framed explicitly around deployment in extreme working conditions — cramped spaces containing obstacles and offering poor lighting — using algorithms based on event-based camera data to map the surroundings. Complementary work has addressed simultaneous localisation and mapping for autonomous drone navigation in these environments.

7.3. Artificial Intelligence in Material Identification and Recovery Planning

A parallel line of enquiry concerns the automated recognition of recoverable materials. Optical recognition systems employing multi-band scanning and neural networks have been reported to classify structural steel, copper wiring and aluminium fittings at accuracy rates exceeding ninety-five per cent, including for degraded or painted materials, while robotic disassembly units directed by adaptive control and sensor feedback execute cutting and sorting

autonomously, reducing worker exposure to asbestos and heavy metal residues. Analytics platforms drawing on historical vessel documentation, maintenance archives and commodity databases have additionally been applied to forecasting material recovery potential and the residual functionality of salvaged equipment [59].

Decision support at the fleet level represents a further application. A machine-learning framework evaluating the trade-off between continued vessel operation and recycling for residual steel value has compared Long Short-Term Memory networks against ARIMA, VAR/VECM and GARCH specifications in forecasting dry bulk freight rates and steel scrap prices, with the LSTM outperforming the econometric benchmarks across vessel classes and forecast horizons. The occupational relevance of such work is indirect but real: improved anticipation of recycling volumes would allow yards to plan workforce deployment and hazardous waste handling capacity in advance rather than absorbing demand shocks through intensified manual working [60].

7.4. Repositioning Recycling within Lifecycle Sustainability

A final development concerns the framing of recycling itself. Recent work applying a PRISMA-based methodology to literature from 2019 to 2025 has reframed merchant ship recycling as a front-end pillar of maritime decarbonisation through the assessment of embodied carbon trade-offs, arguing that the disconnect between shipbuilding hubs and recycling regions necessitate a shift toward extended producer responsibility, and that material traceability together with design-for-recycling principles are essential if recycling facilities are to become high-technology carbon-abatement hubs rather than sites of externalised harm [61].

7.5. Research Agenda

Four priorities follow from the foregoing. First, the technologies described above have been developed almost exclusively within European institutional and infrastructural settings, and their transferability to intertidal beaching operations in Bangladesh, India and Pakistan is untested; research establishing whether drone-based hazardous material survey and tele-operated cutting can function on tidally inundated, unpaved working platforms is a precondition for any benefit reaching the workforce most at risk. Second, the occupational effect of partial automation requires empirical evaluation rather than assumption, since the displacement of workers from cutting operations may redistribute rather than eliminate risk. Third, the capital intensity of these systems stands in direct tension with the cost structure that sustains the beaching method, and techno-economic assessment establishing viable adoption pathways — including phased, low-capital interventions such as wearable gas and particulate monitoring — is required. Fourth, the integration of digital traceability with the Convention's certification machinery represents an opportunity to make compliance continuously verifiable rather than periodically inspected, and the regulatory and technical design of such integration remains substantially unexplored.

8. CONCLUSION

This review paper has comprehensively studied ship recycling practices in major facilities, centering on the critical perspectives of occupational safety and health. The aim of this study was multifaceted, including assessing regulatory frameworks, analyzing environmental and occupational health impacts, identifying research gaps, and proposing strategies for strengthening occupational standards in ship recycling destinations. Employing a systematic review methodology, meticulous data were gathered from prominent databases like "Science Direct", "Springer," and "Research Gate," scrutinizing the occupational safety standards prevailing in major ship dismantling destinations from 2008 to 2024.

Throughout this article's exploration, significant developments in the realm of research on the health and occupational safety aspects of ship recycling were unearthed. Initially, the findings underscored the recognition of challenges inherent in the industry, with subsequent studies exploring more specific issues and presenting innovative solutions. Particularly significant is the growing emphasis on green or safe and environment-friendly compliant ship recycling, a trend further accentuated by the entry into force of the Hong Kong Convention on 26 June 2025. This regulatory framework has catalysed efforts towards promoting environmentally sustainable practices within the ship recycling sector.

The comparative analysis undertaken in this review indicates that the five recycling nations occupy markedly different positions on this trajectory, and that dismantling method operates as the principal upstream determinant of occupational risk. It further indicates that formal regulatory adoption and operational implementation are separated by a substantial interval, most visibly in Bangladesh, and that the distribution of research effort across the five nations correlates with, and plausibly reinforces, the gradient in documented safety performance. On this basis, the following recommendations are directed to the four constituencies whose action the findings implicate.

For policymakers in recycling states, ratification should be treated as the commencement of obligation rather than its discharge. The disproportion between certified facility numbers and workforce size, particularly acute in Bangladesh, indicates that certification capacity itself requires public investment: accreditation bodies, inspectorate staffing, and hazardous waste treatment and disposal infrastructure downstream of the yards, without which facility-level compliance cannot be completed however willing the operator. Incentive structures that lower the capital barrier to yard upgrading — concessional financing, tariff treatment of imported containment and handling equipment, and phased compliance timetables tied to verified milestones — are likely to accelerate diffusion more effectively than sanction alone, as the Indian experience of certification spreading across 106 facilities suggests. Policy attention is also warranted in Pakistan, where the absence of any certified facility combines with the thinnest evidence base of the five nations to produce a situation in which neither reform nor its absence is presently documented.

For the ship recycling industry, the recurrence across more than a decade of the same failure modes — residual gas explosions during hot work, falls from height, and absent first aid and emergency response provision — establishes that these are systemic rather than incidental. Priority should accordingly attach to gas-freeing verification before hot work, competent-person confined space entry procedures, fall protection on elevated cutting positions, and functioning on-site emergency response and evacuation capability, none of which are technologically demanding relative to their demonstrated effect. Beyond this baseline, the operational lesson emerging from the comparison is that infrastructural containment and human-factors intervention are complements rather than alternatives: the Chinese alongside method and the Turkish emphasis on training-needs assessment and preventative risk modelling each address a failure mode the other leaves unaddressed. Yards pursuing certification would be advised to treat the Ship Recycling Plan as an operational planning instrument rather than a documentary requirement, since its value lies precisely in the anticipatory identification of hazards before cutting commences.

For maritime authorities, classification societies and flag states, the two-tier compliance environment created by the differing requirements of the Convention and the European Union Ship Recycling Regulation invites regulatory arbitrage at the point of vessel sale, and warrants coordinated attention. Verification practice merits particular scrutiny: the reviewed literature offers little assessment of whether certified status corresponds to sustained rather than episodic conformity, and the credibility of the certification regime now that it carries legal consequence depends upon resolving this. Authorities are further positioned to require that the Inventory of Hazardous Materials be maintained as a verified lifecycle record rather than compiled at disposal, and to extend cash-buyer transparency so that the beneficial ownership of vessels at the point of sale for recycling is ascertainable.

For researchers, four priorities follow from the gaps identified in Sections 6 and 7. Longitudinal epidemiological study of workers and adjacent communities remains the most significant outstanding requirement, since the long-latency consequences of asbestos and heavy metal exposure cannot be established through the cross-sectional designs that predominate in the reviewed corpus. Evaluation of training effectiveness, as distinct from training provision, is similarly underdeveloped across all five nations. The evidentiary imbalance itself requires redress, with Pakistan the clearest case. And the emerging technologies examined in Section 7 — drone-based hazardous material survey, digital twin recycling planning, tele-operated cutting, and blockchain-enabled waste traceability — require testing for transferability to intertidal working conditions, together with techno-economic assessment establishing viable adoption pathways for yards operating on South Asian cost structures.

Looking ahead, the need for continued research remains pressing in two domains identified throughout this review: enhancement of hazardous material management to ensure the holistic well-being of workers engaged in ship recycling operations, and evaluation of workers' training methods across the regions and their effectiveness. The incorporation of advanced technological features — the application of 3D ship cut models across South Asian facilities for hands-on practical understanding of the workforce, technology-driven training modules delivered through virtual reality, centralised web-based training systems, and modern ship cutting sequences and safer material handling machinery — will be key considerations for creating change going forward. These features and technological solutions can be integrated with research studies for practical implementation of techno-economic developments within the global ship recycling industry. Addressing these critical research gaps holds immense promise for cultivating safer, more sustainable, and economically viable ship recycling operations globally. Through collaborative efforts and interdisciplinary approaches, stakeholders and researchers engaged can collectively propel the industry towards a brighter and safer future.

ACKNOWLEDGEMENT

This paper is the outcome of the project funded by Engineering X, an international collaboration founded by the Royal Academy of Engineering and Lloyd's Register Foundation. This project is being carried out as part of the Engineering X Safer End of Engineered Life mission.

CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHORSHIP CONTRIBUTION

Shaumik Sharif Dipto: Writing – original draft & literature review, **Shaikha Shohuda Tuktuk** – Writing - original draft & literature review **N.M. Golam Zakaria:** Review & editing, Supervision, Conceptualization. **Zobair Ibn Awal:** Review & editing, Supervision, Conceptualization. **Nafisa Mehtaj:** Review & editing**. M.A. Hannan:** Review & editing, Supervision, Conceptualization. **A.K. Dev:** Review & editing, Project administration, Funding acquisition.

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