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Sociological and Ecological Vulnerabilities from Nuclear Waste Discharge: A Case Study of Fukushima's Marine Ecosystem

Shahnaz Bhutto [1*], Abdul Rasool Khoso [2], Wang Suyuhan [3]
[1-3] Department of Sociology, School of Public Administration, Hohai University Nanjing, China

* Corresponding Author: **Shahnaz Bhutto**

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Abstract
The release of treated nuclear wastewater from the Fukushima Daiichi nuclear power plant into the Pacific Ocean has sparked serious ecological and public health concerns. This research highlights the socio-ecological vulnerabilities of nuclear waste discharges on marine ecosystems and human communities, specifically concentrating on the Fukushima incident. For the purpose, a literature based research was conducted for examining the spreading of radionuclides in marine ecosystems and their gatherings in Human food chain, creating a big hindrances in society as well as health risks to living organisms. Besides that, a general perception from local respondents were also highlighted as a touch to gather information regarding the awareness. The findings indicate that increased volumes of discharged water correlate with worsening conditions in health, environment, social stability, and marine life, underscoring the need for stringent international regulations and effective environmental management. Furthermore, the study highlights that radionuclides such as tritium and carbon-14 pose persistent ecological and health risks due to their long-term presence and bio accumulative properties. In conclusion, the Fukushima seemed to be the example of continuing and complicated disaster on both human life as well as marine ecosystem. Therefore, the study recommends that the reinforced policy frameworks are necessary for preserving high safety standards, ensuring international accountability, and fostering public trust while adhering to global best practices in nuclear safety and environmental protection.

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Keywords: Nuclear Wastewater Discharge, Fukushima, Environment, Health, Marine

1. Introduction

Nuclear contamination has long been a global problem, with a history of disastrous catastrophes. Three Mile Island tragedy in the United States in March 1979, Chernobyl nuclear power plant catastrophe in the Soviet Union in April 1986, and Fukushima nuclear disaster in Japan in March 2011 are notable instances (Guo *et al*., 2022) [14]. The tragic effects of nuclear radiation, such as the emergence of radiation-related diseases including cancer and genetic abnormalities, have been brought to light by these occurrences (Niazi & Niazi, 2011). Governments, academics, and the general public continue to pay attention to these catastrophes because they routinely cause severe environmental harm in addition to the acute health hazards given by radioactive contamination (Suarez *et al*., 2014). Recent years have seen an increasing danger to the marine ecology from the problem of ocean pollution. The need of protecting the maritime environment is becoming more widely recognized. From a sociological perspective, these events have sparked significant public debates about the safety and sustainability of nuclear energy, influencing policy decisions and the governance of technology. A research by Lotze *et al*., (2018) evaluating public views of ocean-related problems and preventative strategies included more than 32,000 respondents from 21 different nations. According to the study's findings, a sizable 70% of respondents thought that human activities actually posed a harm to the maritime ecosystem. Chen *et al*., (2023) [7]'s research also emphasized the need to strengthen consultation arrangements as a way to support environmental governance and successfully manage the escalating environmental concerns.

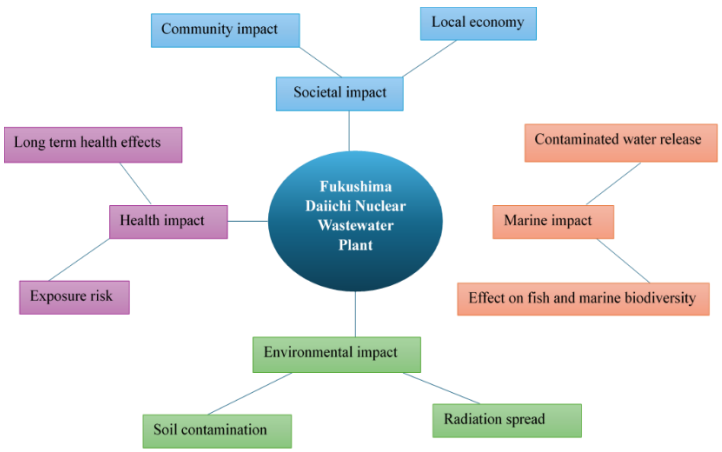
Following the Fukushima nuclear catastrophe in Japan on March 11, 2011, TEPCO (Tokyo Electric Power Company) has been using saltwater injection as a cooling solution for the reactors at the Fukushima Daiichi Nuclear Power Plant to prevent a meltdown (Periáñez, 2022). Due to groundwater and precipitation intrusion, a sizeable volume of radioactive effluent has built up inside the facility over time. The water storage tower is anticipated to reach its maximum capacity in the summer of 2022, according to TEPCO, it has a total capacity of 1.37 million tons (Guo *et al*., 2022) [14]. The Japanese government announced plans on April 13, 2021, for a 40-year-long slow release of some 1.26 million tons of radioactive effluent from the Fukushima Daiichi radioactive Power Plant into the Pacific Ocean. While, one kilometer offshore, the discharge procedure is expected to start in 2023 (Normile, 2021; Yang *et al*., 2021). Concerns have been expressed regarding putting domestic nuclear safety ahead of the wellbeing of the world's marine ecosystem, which is a shared resource, as a result of Japan's proposal to release radioactive effluent from the Fukushima Daiichi nuclear power plant into the Pacific Ocean (Wang *et al*., 2023) [23].

However, the post-Chernobyl era is largely responsible for the current international legal system addressing culpability and compensation in nuclear accidents (Burns, 2012) [6]. The current international legal system has shortcomings that prevent it from adequately protecting transboundary victims and managing the hazards posed by marine nuclear contamination. This is because Japan's radioactive water discharge has the potential to pollute the ocean. Bunn and Heinonen (2011) [30] noted that "these institutions still largely leave decisions on nuclear safety and security measures to individual countries, with only broad and voluntary international standards in place and limited authority for global organizations like the IAEA." The Fukushima tragedy and its wastewater disposal strategy highlight the need for a legislative framework that compels nuclear operators and nations with nuclear plants to take international accountability for nuclear accidents while also supplying prompt responses and adequate compensation mechanisms (Wang *et al*., 2023) [48]. The Fukushima accident highlights the need for sovereign governments to sincerely embrace their obligations to uphold international environmental protection standards when pursuing nuclear power. It is suggested by Nottage *et al*. (2014) that "the legal aspects of disaster management also involve issues of proactive regulatory design." The international legal system can only properly carry out its regulatory task when maintaining maritime environmental protection is seen of as being as important as, if not more important than, the economic benefits received from utilizing nuclear energy.

1.1 Nuclear sewage and its impacts on public health and environment

Nuclear wastewater discharge seriously threatens human health, marine environment and ecological safety. The planned discharge of nuclear wastewater from Japan's Fukushima Daiichi nuclear power plant into the Pacific Ocean has sparked significant concerns over its potential impacts. Following the 2011 nuclear disaster, the contaminated water has raised environmental issues, including worries about radioactive substances affecting marine ecosystems and seafood. There are also health concerns related to consuming potentially contaminated seafood. It's important to understand that no filtration method can completely remove all radioactive pollutants, as stated by Buesseler (2020) [4]. Tritium, carbon-14, cobalt-60, and strontium-90 are among the isotopes found in the Fukushima nuclear disaster's treated effluent (Maki *et al*., 2019). Tritium stands out owing to its unusual properties as a helium isotope that doesn't readily absorb into biological things and its very short half-life of slightly over 12 years (Eidemüller, 2021) [9]. Tritium also seldom settles into sediments since it is mainly an inert gas. In contrast, carbon-14 has a half-life that is 5,700 years long in human terms, is easily absorbed by living things, and is trapped in sediments on the bottom (Kutschera, 2018) [19]. These isotopes may be harmful to human DNA, especially if they build up in marine species and go up the food chain. In this process of accumulation, the length of the food chain is key; longer food chains have stronger aggregation effects, which eventually have an impact on human health (Lu *et al*., 2021). Transparency and international consultation have been points of contention, with some countries seeking more information about the disposal process. Japan intends to treat the water to reduce radioactive contaminants and closely monitor its environmental effects, while international reactions to this plan have been mixed, reflecting a complex and ongoing debate over managing nuclear wastewater.

1.2 Conceptual framework for the study



Source: authors own idea

Fig 1: Conceptual Framework

The research overall highlights the socio-ecological impacts of Fukushima Daiichi nuclear waste water treatment. Therefore, the research includes a conceptual framework focusing on health, environmental, societal and marine impacts. This figure specifically highlights the impacts relying over the health including long term health effects as well as exposure risks, environmental impact specifically on soil contamination and radiation spread. While, marine impact focusing effects on fish and marine biodiversity and contaminated water release. So far, the overall societal impacts were highlighted on community as well as the local economy. This visual tool is instrumental in understanding the full scope and intricate connections of the incident's consequences, making it a valuable resource for academic purposes to encapsulate complex interactions in a digestible manner.

1.3 Statement of problem

Since the tragic events of March 2011, Japan's Fukushima Daiichi Nuclear Power Plant has been a significant source of environmental and safety worries. The release of radioactive effluent into the Pacific Ocean is the main problem. The Fukushima Daiichi Nuclear Power Plant catastrophe, which was brought on by a strong earthquake and tsunami and resulted in the discharge of radioactive materials into the environment, is the cause of this issue (UNSCEAR 2020/2021). These toxins have built up over time as polluted water on the plant's property, necessitating a management strategy. There is an urgent need for an alternate strategy since Tokyo Electric Power Company Holdings (TEPCO) has been holding this polluted water in on-site storage tanks that have now exhausted their storage capacity restrictions (Abolhosseini *et al*., 2014) [28]. For tackling the storing concern, Japanese government and the TEPCO have discussed the proposal regarding the nuclear waste water discharge containing specific radioactive isotopes, into the Pacific Ocean (Suto *et al*,. 2013). While, the idea has created a big debate including both domestic as well as the foreign activist raising voices about the concerns. The concerns were relying over the discharge of waste water over the health effects as well as environmental concerns (Liao *et al*., 2023; Xiao *et al*., 2023) [49]. SO far, the voices from different nations have also been raised specifically south Korea and China regarding the Nuclear waste water discharge, who were well aware about the hazards and were worried about the pollution that could be fetched to the sea food supply, marine eco system and larger implications for regional and international safety standards (Yamaguchi *et al*., 2022). As, these both nations utilize sea food at greater extent. For solving such concern and reducing the hazards from environment and health that is produced by the discharge, diverse stakeholders were of the opinion to call for the investigation of other approaches to the wastewater problem, such as offshore deep-well injection or extra on-site storage (IAEA, 2015) [18]. It is crucial to address the nuclear sewage discharge from the Fukushima Nuclear Power Plant in a way that prioritizes environmental responsibility and transparency while ensuring the safety and well-being of nearby communities, marine ecosystems, and international partners in light of these numerous difficulties and worries (Datta, 2023; Lee *et al*., 2023) [33, 46]. Therefore, the researcher is of the opinion to highlight the concern on local as well as international level particularly a sociological inquiry of the vulnerability of the marine ecosystem and the environment as a result of the discharge of nuclear waste. The study will concentrate on comprehending the ecological and human aspects of vulnerability in the Fukushima using secondary analysis, illuminating the long-term effects of this intricate calamity.

2. Methodology

2.1 Identification of data sources

We obtained our data from well-established scientific repositories that are recognized for their strict standards and relevance to environmental and sociological studies. The sources included: **PubMed**: for research related to the health effects of environmental factors. **Web of Science**: for a broad array of peer-reviewed academic writings. **Scopus**: offering a comprehensive collection of scientific papers, allowing for extensive data coverage.

2.2 Search Methodology

Our approach to data gathering was methodically designed to select the most pertinent and up-to-date information on the impacts of nuclear waste. We employed specific search terms combined with Boolean logic in our queries. The main search terms were "Fukushima", "Nuclear", "waste water", "Health impacts", "Environmental", and "Marine life". These terms were linked with Boolean operators such as AND and OR to perform an exhaustive search, for instance, "Fukushima AND Nuclear AND waste water AND Health Impacts AND Environmental AND Marine life". We limited our search to studies published within the last decade to ensure the data's current relevance. The search was performed in English and included various types of scholarly outputs like articles, reports, and conference papers to capture a broad spectrum of academic input.

2.3 Criteria for data selection and extraction

The criteria for selecting studies included: Focus on the environmental or health effects of nuclear wastewater. Involvement of data or case studies related to marine ecosystems. Inclusion of only peer-reviewed studies published in English.

2.4 Analytical Approach

For our quantitative analysis, we employed regression analysis to assess the connection between the volumes of nuclear wastewater discharged and the indices of various impacts (health, social, environmental, marine). The regression equation applied was:

$$y=ax+b$$

Here, **y** represents the impact index for each category, **x** denotes the volume of discharged nuclear wastewater, **a** is the coefficient indicating the effect of each unit increase in wastewater discharged, and **b** represents the baseline index without any discharge. Statistical evaluations were performed using SPSS Version 25.0. We conducted thorough data verification and consistency checks, including the management of missing data and anomalies. The results were further validated against existing studies to ensure accuracy and dependability.

3. Results

Table 1: Impacts of Fukushima Nuclear Waste water on diverse Components

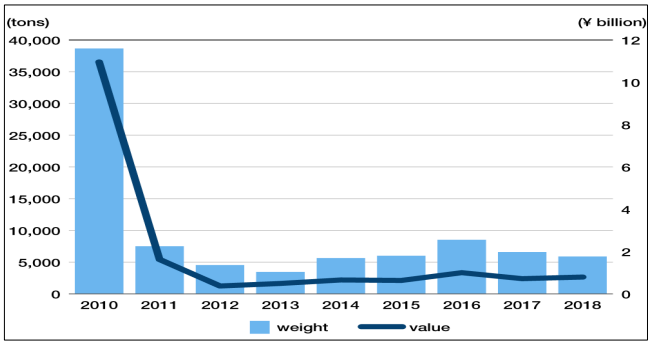
Impact Index	Coefficient	Intercept
Health Impact Index	0.02034	-0.06377
Environmental Impact Index	0.02995	-0.05502
Social Impact Index	0.01515	-0.04033
Marine Life Impact Index	0.02499	-0.07158

This analysis of the regression in table-1, concerning the effects of releasing nuclear waste water from the Fukushima incident shows that the coefficients for the Health Impact Index (0.02034), Environmental Impact Index (0.02995), Social Impact Index (0.01515), and Marine Life Impact Index (0.02499) denote the incremental increase in each impact per cubic meter of waste water discharged. The positive nature of these coefficients demonstrates that each area measured—health, environment, social, and marine life—worsens with higher volumes of discharged water. Notably, the Environmental Impact Index, with the highest coefficient, is the most affected by variations in discharge volumes. The intercepts, such as -0.06377 for health and -0.07158 for marine life, usually indicate the initial impact levels at zero discharge, although negative intercepts might suggest the necessity for model recalibration or might represent negligible initial impacts. These findings underscore the linear correlation between discharge amounts and the resulting negative impacts, emphasizing the urgency to control and reduce these discharges for the welfare of human and environmental health.

3.1 Social impacts of Fukushima nuclear waste discharge on communities

The disaster caused by the Fukushima nuclear has intensely considered to be the hazardous and impacted the diverse international safety standards, local bodies, national policies towards energy and laws as well as ecosystem. At local extent, the disaster has effected the economic activities as well as community structure specifically focusing agriculture, fishery causing social, psychological and health concerns (Schneider, 2023; Yu *et al*., 2023). Nationally, it prompted Japan to reevaluate its nuclear energy strategy, leading to a shift towards renewable energy and stricter safety regulations. Since, policy standards have been deemed to be the concerning regarding the discharge, resulting the disputes over frameworks (Takashi, 2024). On an international level, the incident reinvigorated global discussions on nuclear safety, influencing policies in various countries and enhancing international collaboration through agencies like the IAEA to improve nuclear safety measures worldwide (Ferreira *et al*., 2024) [11]. So far, most of the part of communities have been affected by the discharge not only the economically but also the health perspectives (Lehtonen, 2023) [22]. These changes underscore the complex interplay between technological risks and sociological impacts in managing nuclear energy.

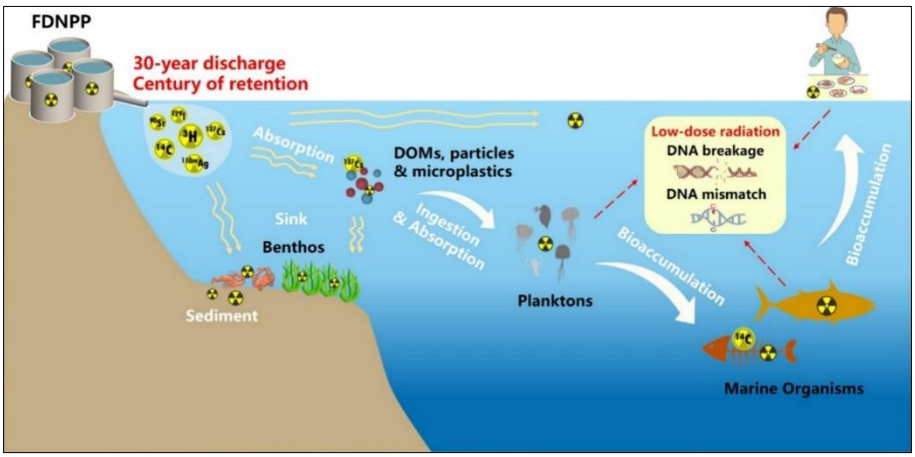
3.2 Fukushima waste water and its impacts over economy



Source: (Nippon.com 2020)

Fig 2: Weight and value of Fukushima prefecture catches

The Figure-2 depicts a significant drop in both the mass and market economic value of fish caught by the Fukushima Prefecture post the 2011 earthquake and tsunami, followed by a slow recovery. Pre-crisis, the catches weighed in at 38,600 tons with a market value of ¥11 billion. The catastrophe caused a stark decline in these numbers, with the subsequent years showing only a modest rebound. By 2018, the industry saw a catch weight of 5,900 tons, amounting to a value of ¥0.796 billion, indicating a substantial reduction from the levels seen before the disaster. SO far, the Fukushima nuclear waste water had a negative impact on the economy of residents in terms of loss of fishery and related business, resulted in socio-economic status considered lower at greater extent.

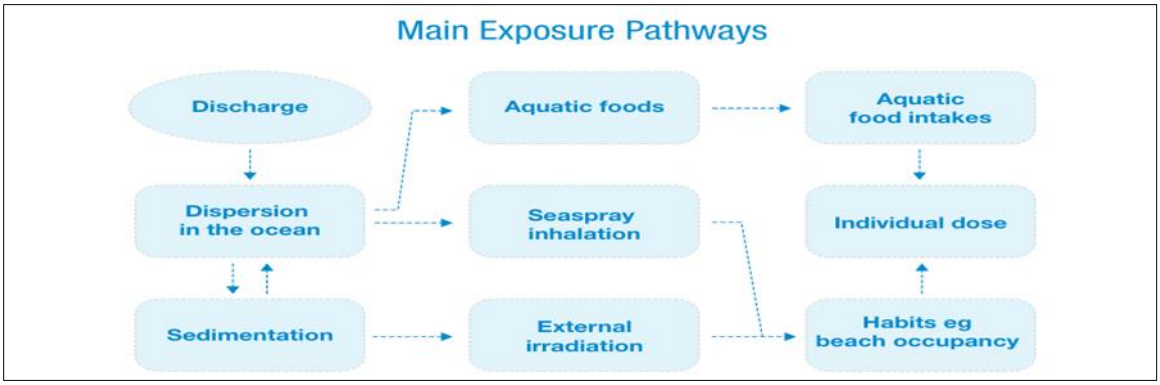


Source: (Wang *et al*., 2024)

Fig 3: From Ocean to Organism: Tracing the Pathway of Nuclear Contamination in Marine Ecosystems

With regards to the environmental contamination and public health, the fig-3 presents a sequence of environmental interactions following the release of nuclear contaminants into the ocean. It starts with the discharge from a nuclear power plant, which releases radioactive elements that disperse in the marine environment. These elements can be absorbed by oceanic sediments, impacting benthic life. Furthermore, marine species, including plankton, may ingest these contaminants along with micro plastics, leading to their accumulation within the food web. As larger marine organisms consume contaminated prey, the radioactive substances bio accumulate, which could result in genetic damage over time. This bioaccumulation eventually extends up the food chain to humans, who may face health risks from consuming affected seafood, highlighting the complex and far-reaching implications of nuclear waste on marine ecosystems and human health (Wang *et al*., 2024).

3.3 Main exposure pathways of Fukushima nuclear waste water discharge plant

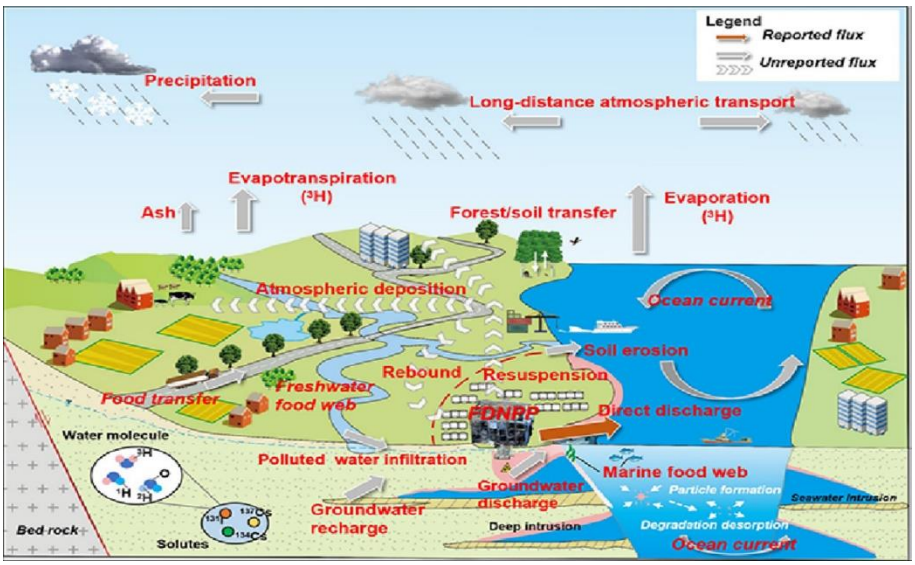


Source: (IAEA, 2023)

Fig 4: Main Exposure Pathways

The Figure-4 depicts the complex path of pollutants from their discharge into the ocean to exposure by humans. Initially, these pollutants sink to the seabed or are absorbed by marine organisms, entering the alimentary chain and possibly being consumed by humans. Sea spray, which contains these pollutants, poses a respiratory risk to those living along the coastline. Consuming contaminated seafood and inhaling polluted sea spray both increase a person's radiation to these contaminants (Giri *et al*., 2024) [37]. Furthermore, external factors such as the amount of time worked near the shore can increase exposure risks (Eze *et al*., 2024) [10]. The illustration uses drawn lines to represent the subcutaneous routes by which these pollutants contribute to an individual's total exposure, enclosing the various pathways of pollution to the environment.

3.4 Environmental and marine impact cycle of radioactive pollution



Source: (Lu *et al*., 2021)

Fig 5: Environmental and Marine Impact Cycle of Radioactive Pollution

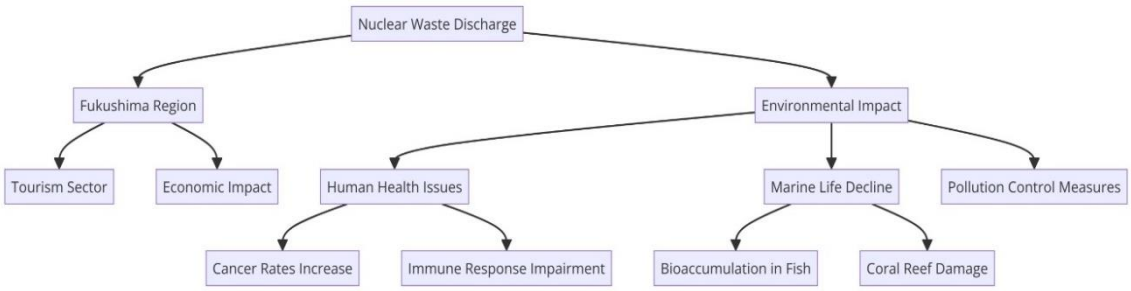
The figure-5 depicts the complex routes through which environmental pollution spreads, with a particular emphasis on the diffusion of radioactive contaminants following an incident like the Fukushima Daiichi nuclear disaster. As articulated by the Lu *et al*., (2021) that, how the pollutants can be shifted from the nuclear plant specifically by soil, air and water by direct flow of water, soil contamination as well as impressive confession. Later, those impurities not only affect the environment surrounding local bodies but also marine life through diverse strategies: radioactive isotopes are transported into ecosystems by precipitation and evapotranspiration, which further harm the water related food

as well as land; oceanic and groundwater currents distribute these contaminants widely, affecting marine biodiversity and potentially entering the human diet via seafood; and soil erosion pushes more pollutants into rivers and lakes, posing additional risks to aquatic life (Azman *et al*., 2024) [27]. These concerns highlights the much needed approach to control the water and environmental pollutants, recommending the much need for the careful consideration and well-structured management through policies and its practices to reduce the impact on living organisms (Azman *et al*., 2024) [27].

3.5 Radiotoxicity and health risks

The ongoing debate regarding the risks associated with tritium and other radioactive substances released from Fukushima's treated wastewater remains unresolved. Gwynn *et al* (2024) [15] articulated that, if the radionuclides are of a low level, even though those can have quantifiable hazards on marine ecosystems and human health (Gwynn *et al*., 2024) [40]. Tritium, a weak beta emitter, can convert into organically bound tritium, which persists in biological systems and may pose greater risks to living organisms (Atzrodt *et al*., 2018) [1]. Taking account an example, the exposure of low level doses radiation can be yoked to alterations in gene regulation, damage in DNA and cellular repair mechanisms. On the pace of time, these cellular changes could boost the risks of dangers in genetic occurrences as well as cancers (Yang *et al*., 2024). Another significant concern is the bioaccumulation of radionuclides within marine food chains. Elements such as cesium, iodine, and strontium can accumulate in marine organisms, eventually entering the human diet through seafood consumption (Sivaperumal *et al*., 2020). These progressions produces the important health dangers specifically for the local bodies which are heavily depending on the sea food as a staple food. While the long-term health effects of low-dose radiation exposure from both natural and artificial sources remain a subject of ongoing scientific investigation, concerns persist regarding its potential impacts on human health (Howard, 2020). Particularly concerning are the unpredictable effects of radiation from ions, which include haphazard DNA mutations that can result in cancer and genetic disorders. It is suggested that any additional radiation exposure, especially for populations and ecosystems that are vulnerable, should be taken very seriously because there is no generally acknowledged safe threshold for these stochastic effects.

3.6 Concepts Interpreting from Literature Review results



Source: authors own concept interpreting literature reviews

Fig 6: Nuclear waste discharge from Fukushima and its impacts

The figure-6 presents a structured analysis of the consequences of releasing nuclear waste, categorizing them into two primary areas: effects on the Fukushima region and broader environmental impacts. In the Fukushima region, the concerns center around two main areas. The tourism industry likely faces a decline as fears of radiation deter visitors, negatively affecting local businesses and services. Additionally, the economic impact is significant, with a decrease in property values, increased healthcare expenses from radiation-related illnesses, job losses in several sectors, and an overall economic slowdown due to the region's negative perception. In addition, the discharge of nuclear wastewater has contributed to a decline in fishery income. Data also highlight specific health concerns in Fukushima, including a potential rise in cancer rates, which may be linked to prolonged exposure to ionizing radiation. Such radiation can damage DNA, increasing the likelihood of mutations that may lead to cancer. Additionally, evidence suggests that exposure to radioactive elements could weaken immune responses, making individuals more susceptible to infections and other illnesses.

So far, speaking about the ecological perspective, the discharge on nuclear waste water could produce some critical disruptions in marine life and its associated eco system. A decline in marine populations has been observed, possibly due to the direct toxicity of radioactive substances, changes in water quality, or disturbances in the food chain. Bioaccumulation remains a critical concern, as fish and other marine organisms absorb and concentrate radioactive particles in their bodies, posing risks to both aquatic life and humans who consume contaminated seafood (Mukherjee *et al*., 2021). The degradation of coral reefs, which play a crucial role in marine biodiversity and coastal protection, further underscores the environmental threats associated with radioactive pollution (Painter *et al*., 2023). For alleviating these concerns, the strategies including pollution control, strict laws, and regulatory frameworks are as essential as to live on earth. Generally, such measures are important for highlighting the concerns fetched by the nuclear waste discharge, in terms of critical evolution through comprehensive safeguards to protect both human health and the environment.

3.7 Fukushima nuclear waste water plants and its impacts on communities

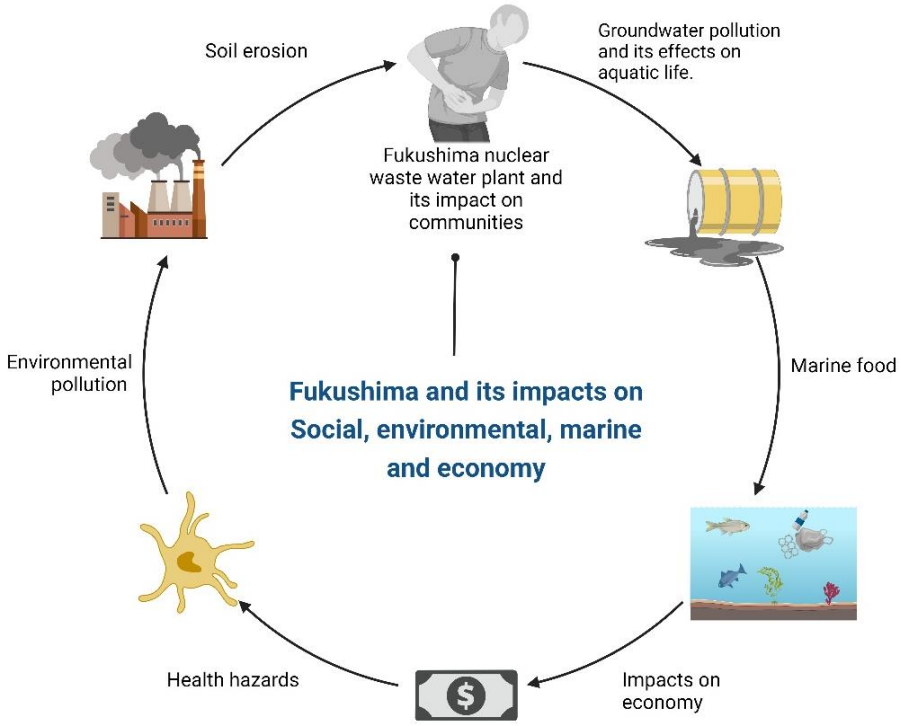


Fig 7: Nuclear waste water and impacts on Community

This diagram-7 provides a visual representation of the wide-ranging effects of the Fukushima nuclear disaster on different facets of life and the environment. At the center of the diagram, the main theme is labeled "Fukushima and its Impacts on Society, Environment, Marine Life, and Economy." Five arrows extend outward, each directing attention to a smaller diagram that represents a specific consequence. Starting from the top right and moving clockwise, the first section, "Groundwater Contamination and Its Impact on Aquatic Ecosystems," is illustrated with an image of a leaking barrel discharging pollutants into a body of water, symbolizing the threat to marine life. Next, the "Marine Food" section features depictions of various sea creatures, reflecting concerns about seafood safety and availability following the disaster. The third section, "Economic Impacts," is represented by a dollar sign, emphasizing the financial strain on local industries and potential economic repercussions beyond the immediate region. In the bottom left, "Health Hazards" are symbolized by a radiation hazard graphic, illustrating the spread of radiation and its potential risks to human well-being. Finally, "Environmental Degradation and Soil Erosion" is depicted through an image of industrial emissions, suggesting that pollution from the disaster contributes to land degradation. Collectively, the diagram effectively illustrates the interconnected consequences of the Fukushima disaster across multiple sectors.

3.8 International nuclear safety standards and environmental governance

The management of nuclear wastewater at the Fukushima Daiichi Nuclear Power Plant is governed by a framework of international nuclear safety standards and environmental regulations (Gong, 2024) [38]. This system involves collaboration between global institutions such as the International Atomic Energy Agency (IAEA) and domestic regulatory bodies like Japan's Nuclear Regulation Authority (NRA) (Liu & Hoskin, 2023) [50]. While the IAEA provides safety guidelines and conducts reviews, its recommendations only become legally binding when incorporated into national laws (IAEA, 2023) [17]. Japan adheres to these international principles through its commitment to agreements such as the Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management and Radioactive Waste Management (Li & Wang, 2023) [23], which emphasize strict safety and environmental protection standards.

The strategy for managing the waste water in Fukushima contains an incessant evolution and monitoring (Lawless & Moskowitz, 2024) [45]. Nevertheless, the tactic has glinted the debate on International level with the aim focusing on the need for inclusive transboundary environmental impact assessments. Such anxieties highlights the extent level of issues regarding nuclear waste management, where, the advancement of ecological, health, economic and technological, deliberations must be well-adjusted (Richter *et al*., 2022). Despite ongoing efforts to ensure safety, skepticism persists, fueled by TEPCO's past transparency issues and uncertainties surrounding the long-term environmental impact.

4. Discussions

The findings from this study emphasize the extensive and complex impacts of nuclear waste discharge on marine ecosystems and human communities, as illustrated by the Fukushima Daiichi incident. Our analysis underscores the significant sociological and ecological vulnerabilities created by such discharges, particularly in terms of health, environmental integrity, social structures, and marine life.

These impacts are exacerbated by the bioaccumulation of radionuclides like tritium and carbon-14, which integrate into marine and human food chains, posing prolonged ecological and health risks. Research by Thakur & Kumar (2024) and Kalita & Baruah (2020) highlights the distinct challenges associated with radioactive isotopes, particularly their extended half-lives and capacity to enter the food chain, leading to long-term ecological and environmental consequences. The sociological impact of the Fukushima disaster is profound, with affected communities experiencing psychological distress, economic hardships, and social instability. Tierney & Oliver-Smith (2012) emphasize these challenges, detailing the prolonged recovery process and the necessity for robust social support systems to aid affected populations. These local disruptions also have broader implications, influencing national energy policies and prompting a reassessment of global nuclear safety standards (Abdin, 2024).

The international response to Japan's management of the Fukushima disaster underscores global concerns regarding nuclear safety and the effectiveness of current regulatory mechanisms (Shiroyama, 2015; Hayashi & Hughes, 2013). Our analysis aligns with these perspectives, reinforcing the need for a critical reassessment of nuclear energy policies and international safety protocols.

A regression analysis of health, environmental, social, and marine life indices reveals a direct correlation between increased nuclear wastewater discharge and worsening conditions in each category. These findings align with Ferenbaugh *et al*. (2002), who demonstrated that even low-level radionuclide exposure can have tangible consequences for public health and ecosystems. The observed relationship underscores the necessity for immediate strategic interventions to mitigate these risks.

Furthermore, concerns about the adequacy of existing regulatory frameworks have been widely debated. Gong (2024) [38] highlights the need for a more comprehensive international legal framework to address the transboundary effects of nuclear waste. Similarly, Bunn & Heinonen (2011) [5] critique the voluntary nature of international nuclear safety standards, advocating for stricter, enforceable regulations to enhance global nuclear security.

4.1 Limitations

This study offers a detailed examination of the ecological and societal effects of nuclear waste discharge, with a particular focus on the Fukushima Daiichi incident. However, several limitations should be acknowledged:

The research highlights the sociological and ecological effects of nuclear waste discharge focusing on Fukushima Daiichi Incident. While, there are some several limitations including: the research mainly rely on the literature review which could not fully capture the scenario of the concern related to the waste impacts. Methodologically, the research has just concentrated over the regression analysis on small scale, while, the large scale data and in-depth interviews could enhance more clarity and broaden the research.

Limited Generalizability – The focus on the Fukushima disaster may limit the applicability of findings to other regions, as geographical, socio-economic, and political differences can influence nuclear waste management outcomes. Gaps in Policy and Legal Analysis – While the study highlights the necessity of stronger governance and international cooperation, it does not provide an in-depth assessment of specific policy implementations or the effectiveness of existing international legal frameworks.

5. Conclusions and policy recommendations

The Fukushima disaster underscores the far-reaching and prolonged consequences of nuclear waste discharge on marine ecosystems and human health. This study concludes the penetration of radionuclides flown in the marine ecosystem and diverts to the marine food chains, could contribute health risks at greater extent globally. The results highlights the strict laws and regulatory framework as the need of the time for preserving the waste management activities to protect public health environment as well as economic part of the nations. In addition to this, for addressing the nuclear waste water discharge risks, it is crucial to involve sustainability in monitoring, reporting as well as preservations. So far, the research recommends the strict policies for strengthening the management of nuclear waste water discharge to mitigate health and environmental risks for the sustainable development. Besides that, Enhanced International Cooperation – Establishing an oversight body involving the International Atomic Energy Agency (IAEA) and regional stakeholders to ensure compliance with safety protocols.

Conflicts of Interests: Authors declare no conflict of interests.

Originality of the research: The authors declare that the research is original and is based on secondary analysis cited well. .

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