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Comparative Risk Review of Major Nuclear Disasters: Analyzing Radiation Exposure, Environmental Impact and Health Consequences Across the Worst Accidents

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Abstract: Nuclear disasters have had profound and lasting effects on human health, the environment, and energy policies worldwide. This systematic review examined five major nuclear accidents: Kyshtym (1957), Windscale (1957), Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011)—to analyze their radiation exposure, environmental impact, and health consequences. Using peer-reviewed literature from 2010 to 2025, the study evaluates the severity of radioactive releases, the isotopes involved, affected populations, and decontamination measures implemented. The results indicated significant variations in the magnitude of radioactive emissions, with Chernobyl releasing the highest radiation (5,300 PBq), leading to widespread contamination and long-term health effects, including over 6,000 thyroid cancer cases. Fukushima, despite being classified as a Level 7 event, had a much lower radiation release (520 PBq) but caused severe psychological distress and displacement of thousands of residents. Windscale and Three Mile Island, though lower in severity, had critical implications for nuclear policies and public perception. The study also explores the long-term environmental consequences of these disasters, including soil and water contamination, bioaccumulation of radioactive isotopes, and ecosystem disruptions. Decontamination efforts varied, with strategies ranging from reactor containment and topsoil removal to advanced filtration techniques. The review highlights key lessons in nuclear safety, including the role of human error, inadequate reactor designs, and the effectiveness of emergency response protocols. Findings underscore the necessity of stricter safety regulations, improved reactor technologies, and sustainable energy alternatives to minimize the risks associated with nuclear power. Understanding past disasters is crucial in preventing future nuclear crises and ensuring a more resilient approach to energy production and disaster preparedness.

Keywords: *Nuclear Power Plants; Radioisotopes; Iodine 131; Cesium 137; Chernobyl; Fukushima; Kyshtym; Windscale; Three Mile Island.*

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I. INTRODUCTION

The history of nuclear power has been illuminated by serious accidents that have demonstrated some of the dangers of this energy source. These incidents include Kyshtym (1957), Windscale (1957), Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). Each of these events has provided valuable information about the consequences of nuclear accidents with special significance regarding radiation exposure, environmental impact, and health effects. In the case of Chernobyl, among 237 firemen and CNPP employees examined for acute radiation sickness, 134 showed symptoms. Despite intensive therapy, including 13 bone marrow transplants, 28 died within four months, mainly from myelosuppression. By 2004, 19 more deaths occurred from other causes (Saenko et al., 2011). The Fukushima accident, on the other hand, did not result in any radiation-related deaths but caused serious psychosocial and mental health problems for the evacuated communities (WHO, 2016).

Comparative analyses of these incidents reveal varying degrees of severity in terms of radioactive releases and health outcomes. The Windscale fire, for example, led to the release of radioactive iodine, resulting in the contamination of local milk supplies and an estimated increase in cancer cases over subsequent decades (Min, S., 2018). In contrast, the Three Mile Island accident is considered the most serious in the history of commercial nuclear power plant operations in the U.S. However, it released only a small amount of radiation, which had no impact on the health of plant workers or the public (Othman, Siti., 2019). These events highlight the complex interplay between technical failures, human factors, and emergency response effectiveness in determining the overall impact of nuclear accidents.

II. METHODOLOGY

The study aimed to systematically review major nuclear disasters, focusing on radiation exposure, environmental impact, and health consequences across the most severe incidents.

A. Data Sources

This study reviewed published materials from reputable sources such as Elsevier, Google Scholar, and ResearchGate, ensuring access to a broad collection of peer-reviewed research. It focused on five major nuclear disasters; Kyshtym, Windscale, Three Mile Island, Chernobyl, and Fukushima examining their radiation exposure, environmental effects, health impacts, and decontamination efforts.

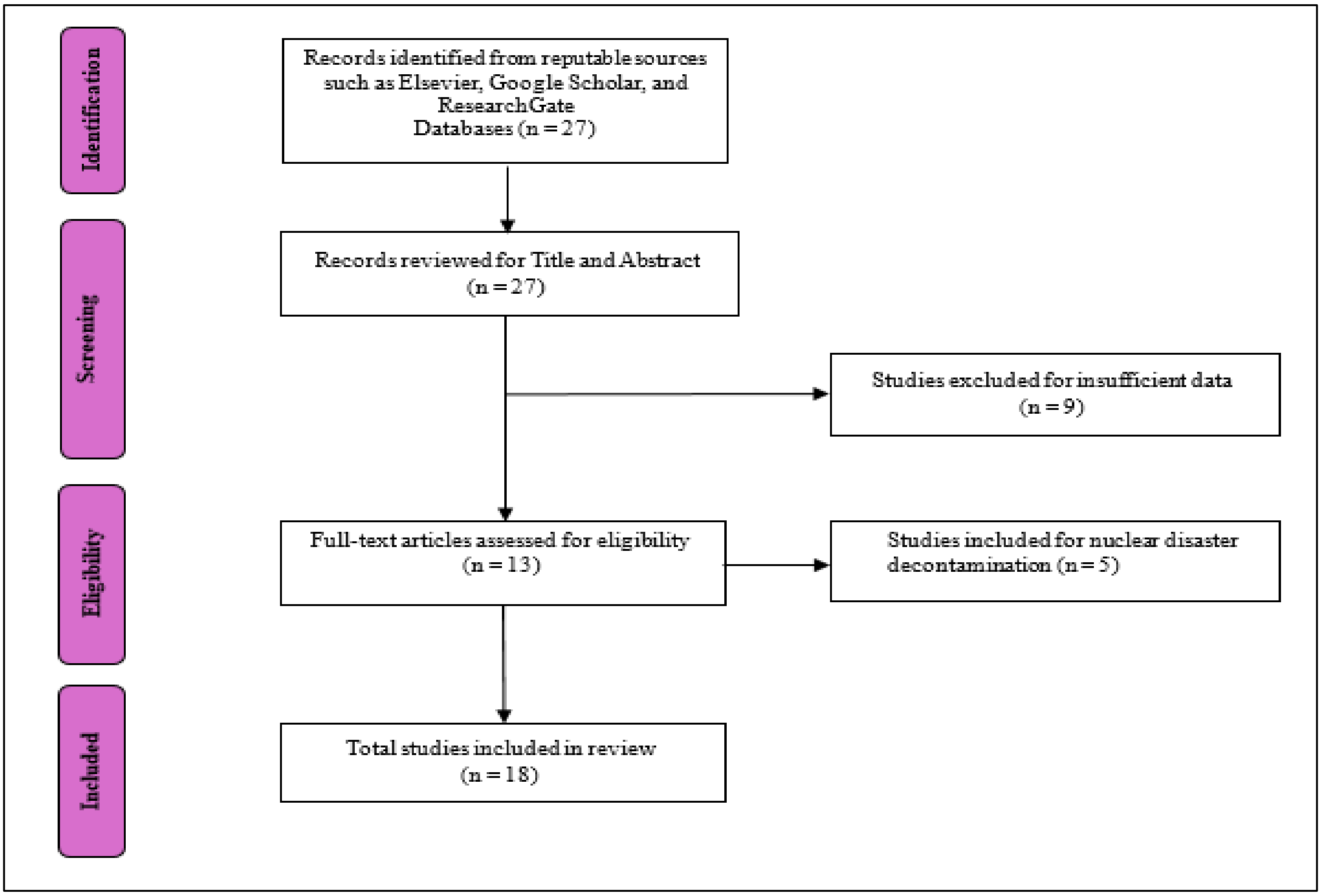

Fig 1: Study Selection Flow Diagram Following PRISMA Guidelines

B. Literature Search

To conduct a comprehensive assessment, the search was divided into three major keyword categories. The first category focused on major nuclear disasters, using keywords such as "Kyshtym disaster," "Windscale fire," "Three Mile Island accident," "Chernobyl disaster," and "Fukushima Daiichi nuclear accident,". These events were selected based on factors such as the cause of the accident, severity level, total radiation release, radioisotopes involved, affected geographical areas, environmental damage, and human health impacts. The second set of keywords focused on radiation exposure and environmental contamination, including terms such as "radiation exposure levels," "radioactive contamination," "cesium-137," "iodine 131," and "environmental consequences of nuclear accidents." These terms ensured the inclusion of studies that evaluate how nuclear disasters affect air, water, and soil quality over time. The third set of keywords focused on the health consequences and long-term risks linked to radiation exposure. It included terms such as "cancer risk from radiation," "thyroid disorders from nuclear accidents," "genetic mutations due to radiation," and "long-term health effects of nuclear disasters." These keywords were chosen to narrow the search to studies that examine the medical and epidemiological impacts of radiation exposure. Additionally, the study considered decontamination efforts for each nuclear disaster.

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To keep the review relevant and up to date, the search was restricted to studies published between 2010 and 2025. The literature search initially included a total of 15 research articles focused on comparative risk assessments of major nuclear disasters.

C. Inclusion and Exclusion

This review considers studies that discuss key aspects of major nuclear disasters, including radiation exposure levels, environmental contamination in air, water, and soil, health effects such as cancer and genetic disorders, and the decontamination measures used to mitigate damage.

Studies were not included if they lacked detailed data on radiation exposure, environmental impact, or health consequences, focused on minor nuclear incidents, primarily addressed policy rather than disaster effects, and had incomplete findings.

D. Search Results

A total of 27 studies were gathered from databases like Elsevier, Google Scholar, and ResearchGate. After screening the titles and abstracts, 9 studies were excluded due to insufficient information on radiation exposure, environmental impact, or health consequences. This left 13 full-text articles for further evaluation. Out of these, 5 studies specifically examined decontamination efforts for different nuclear disasters. The selected papers provided both qualitative and quantitative insights into radiation exposure, environmental effects, and health impacts, meeting the criteria for inclusion.

E. Data Extraction

The study compared five significant nuclear disasters: Kyshtym, Windscale, Three Mile Island, Chernobyl, and Fukushima. These incidents were chosen based on variables such as the cause of the accident, severity, total radiation release, radioisotopes involved, affected geographical areas, environmental damage, and health consequences. Each disaster was evaluated in terms of radiation exposure, environmental impact, and human health impacts in the areas that were affected. The study also assessed the long-term environmental impacts, contamination levels, and response strategies to mitigate these effects. By studying the various disasters, the study aims to provide a comprehensive awareness of the risks involved with nuclear accidents and their global consequences.

F. Statistical Analysis

After reviewing the 18 selected studies, each paper was assessed for its relevance to both quantitative and qualitative analysis. The studies included data on radiation exposure, environmental impact, and health consequences from major nuclear disasters like Kyshtym, Windscale, Three Mile Island, Chernobyl, and Fukushima. The selection process considered factors such as the causes of the accidents, the severity of the events, the total radiation released, the types of radioisotopes involved, the affected areas, and the environmental and health impacts. This comprehensive approach helped combine both qualitative and quantitative findings, ensuring the results were aligned with the study's objectives and provided an in-depth comparison of these major nuclear accidents.

III. RESULTS AND DISCUSSION

A. Overview of Nuclear Disasters

Nuclear disasters have had profound impacts on human health, the environment, and energy policies worldwide. These incidents, often resulting from engineering failures, human errors, or natural disasters, highlight the risks associated with nuclear energy. The severity of these accidents varies, with some causing localized contamination while others have had long-term global consequences.

Table 1 outlines five of the most significant nuclear disasters in history, detailing their causes, severity levels, and the extent of their impact. These disasters illustrate how nuclear incidents can arise due to human error, mechanical failures, poor engineering design, or natural disasters, each leading to varying levels of radioactive contamination and long-term environmental consequences.

The Kyshtym disaster in 1957, which occurred in Chelyabinsk, Russia, is one of the lesser-known but severe nuclear incidents, rated at level 6 on the International Nuclear Event Scale (INES). The accident was caused by a failure in the cooling system of a nuclear waste storage tank, leading to an explosion. The lack of proper engineering design prevented necessary repairs, which ultimately resulted in a buildup of heat and pressure, causing the tank to explode. The radioactive contamination spread over an area of approximately 300 km × 50 km in Siberia, making it one of the largest nuclear contamination zones at the time.

The Windscale fire, which took place in Cumbria, England, in October 1957, is another example of a significant nuclear accident, classified at severity level 5. It was caused by overheating during an annealing process in Pile 1, where Wigner energy was being released. Despite efforts to control the temperature, it reached an alarming 400°C, leading to overheating of fuel cartridges and the outbreak of flames. Attempts to extinguish the fire with carbon dioxide failed, but increased water flow eventually stabilized the reactor. The radioactive contamination reached Cumbria and Lancashire in North-West England, making this one of the worst nuclear accidents in British history.

The Three Mile Island accident, which occurred in Pennsylvania, USA, in 1979, was also rated at severity level 5 and resulted from a combination of human errors, mechanical malfunctions, and questionable instrument readings. A failure in the cooling system caused overheating, leading to partial melting of the reactor core. Although there were limited radioactive releases beyond the plant, the event triggered widespread public fear and concerns over nuclear safety. Pregnant women and small children within an 8-km radius were advised to evacuate, and about two million people within an 80-km radius were estimated to have received a radiation dose of 0.015 mSv. This incident significantly influenced nuclear regulatory policies in the United States.

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The Chernobyl disaster in 1986, which occurred in Pripyat, Ukraine, is widely regarded as the worst nuclear disaster in history and was classified at severity level 7, the highest rating on the INES scale. It resulted from a flawed reactor design combined with human errors during a late-night safety test. The overheating reactor caused a steam explosion, rupturing pipelines and expelling coolant. A subsequent explosion destroyed the reactor, releasing vast amounts of radioactive debris into the atmosphere. Fires ignited by residual heat further prolonged radioactive releases for ten days. The disaster severely affected Ukraine, Belarus, and Russia, causing long-term environmental damage and severe health consequences, including increased cancer rates and birth defects in affected areas.

The Fukushima disaster, which occurred in Japan in 2011, was another level 7 nuclear event, demonstrating how natural disasters can exacerbate nuclear risks. Triggered by a magnitude 9.0 earthquake and a massive tsunami, the incident severely damaged the Fukushima Daiichi Nuclear Power Plant.

Table 1: Overview of Nuclear Disasters

Nuclear Disaster	Date and Location	Cause of Accident (Explosion Type)	Severity Level	Affected Area (Geographical extent)	References
Kyshtym	September 29, 1957 Chelyabinsk, Russia	A coolant leak at the Mayak nuclear facility caused overheating and a pressure buildup.	6	Approximately 300 km x 50 km area of Siberia	Smith, J. T. (2011) Vasilenko, E. K. (2020)
Windscale	10 October 1957 Cumbria, England	A failed annealing process led to overheating and ignition of uranium cartridges	5	Reached Cumbria and Lancashire in North-West England	Min, S. (2018) McNally, R. J. Q., et. al. (2016)
Three Mile Island	March 28, 1979 Pennsylvania, USA	Equipment malfunctions and human errors	5	A temporary evacuation within ~8 km of the plant, while two million people within ~80 km received an estimated 0.015 mSv dose.	Morales Pedraza, Jorge. (2013) Bromet, E. J. (2013)
Chernobyl	April 26, 1986 Pripyat, Ukraine	Reactor design flaws and human errors.	7	Severely impacted Ukraine, Belarus, and Russia, causing lasting environmental and health effects.	Steinhauser, G., Brandl, A., & Johnson, T. E. (2013) Saenko, V. et. al (2011)
Fukushima	11 March 2011 Fukushima, Japan	A 9.0 magnitude earthquake and tsunami flooded the plant, disabling cooling systems, leading to core meltdowns.	7	Led to offshore contamination, Pacific Ocean deposits, and the evacuation of 170,000 residents, including 20,000 voluntarily.	Yoshida, N., & Kanda, J. (2012) Imanaka, T., Hayashi, G., & Endo, S. (2015)

The tsunami, reaching heights of up to 40.5 meters and penetrating as far as 10 km inland, flooded the facility and disabled its cooling systems. The failure of backup generators and water intake structures led to a station blackout, resulting in core meltdowns in multiple reactors. This disaster led to significant offshore contamination in the Pacific Ocean and the evacuation of approximately 170,000 residents, including 20,000 voluntary evacuations.

B. Total Radioactivity Released

The total radiation release from major nuclear disasters varies significantly, highlighting the differing severity and impact of these catastrophic events.

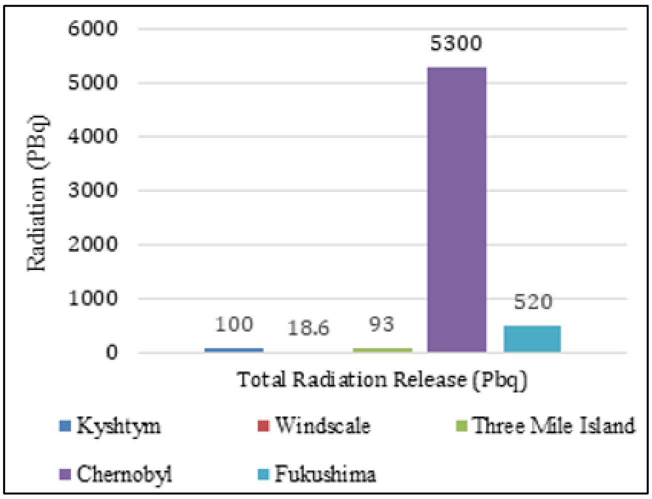

Fig 2: Total Radiation Released of Each Nuclear Disasters

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Figure 2 provides the total radiation release (PBq) from five major nuclear disasters, demonstrating substantial variations in the magnitude of radioactive emissions. Among these incidents, Chernobyl (1986) is by far the most extreme, with a total radiation release of 5300 PBq, an amount that dwarfs all the other disasters. This value is approximately ten times greater than Fukushima (520 PBq), fifty-three times higher than Kyshtym (100 PBq), and fifty-seven times greater than Three Mile Island (93 PBq). Moreover, Chernobyl's radiation release accounts for approximately 85% of the total radiation emitted by all five disasters combined. The steep contrast between Chernobyl and Fukushima suggests that, although both were categorized as Level 7 disasters on the International Nuclear Event Scale (INES), their radiation release varied significantly.

Fukushima (2011) recorded the second-highest radiation release at 520 PBq, which, while still significant, is only 10% of the radiation released by Chernobyl. This substantial difference indicates that the radioactive emissions from Chernobyl were on an entirely different scale. However, Fukushima's release was still over five times higher than Kyshtym (100 PBq) and Three Mile Island (93 PBq), making it the second most severe nuclear disaster in terms of radiation discharge. Fukushima contributes around 8.3% of the total.

Moving further down the scale, Kyshtym (1957) and Three Mile Island (1979) recorded nearly identical radiation releases at 100 PBq and 93 PBq, respectively, differing by only 7%. This close similarity suggests that their radioactive emissions were of comparable magnitude. However, these values are still much lower than Fukushima and exponentially smaller than Chernobyl. The consistency between Kyshtym and Three Mile Island in terms of radiation release makes them appear more moderate in comparison to the top two disasters. Furthermore, Kyshtym and Three Mile Island each represent around 1.5% of the total radiation.

The lowest radiation release among the five events came from Windscale (1957), which emitted only 18.6 PBq. Windscale accounts for just 0.3%. This amount is 99.6% lower than Chernobyl, 96.4% lower than Fukushima, and approximately 80% lower than Kyshtym and Three Mile Island. Windscale's significantly lower radiation release highlights a stark contrast with the other disasters, making it the least severe in terms of radioactive emissions. The difference between Windscale and Three Mile Island, though considerable, is far less pronounced than the gap between Fukushima and Chernobyl.

A drastic peak at Chernobyl, followed by a sharp decline to Fukushima, and then a more gradual drop-off across Kyshtym, Three Mile Island, and Windscale. This pattern underscores the sheer scale of radioactive emissions from Chernobyl, making it an outlier in nuclear disaster history. Fukushima, despite being the second highest, is significantly lower than Chernobyl but still much greater than the remaining three disasters. The progressive decrease from Fukushima to Windscale suggests that the scale of radiation release in nuclear disasters varies widely, with some incidents resulting in minimal radioactive emissions while others lead to catastrophic contamination.

C. Radioisotopes Involved

The releases of Iodine-131, Cesium-137, and Strontium-90, three key radioactive isotopes, are commonly measured in nuclear disasters due to their environmental persistence and significance in radiation exposure. These isotopes are selected for analysis because they contribute heavily to both immediate and long-term contamination. Iodine-131 (I-131) has a half-life of about 8 days and spreads quickly through the atmosphere after a nuclear release (USEPA, 2025). Although it decays rapidly, its high absorption in the human thyroid makes it a critical concern in the short term. Cesium-137 (Cs-137), with a half-life of approximately 30 years, is a long-lived contaminant that dissolves easily in water, leading to widespread soil and water contamination. This isotope remains in the environment for decades, prolonging radiation exposure risks. Strontium-90 (Sr-90), also with a half-life of about 30 years, behaves similarly to calcium, allowing it to accumulate in bones and teeth. This characteristic makes it particularly hazardous for long-term biological exposure. While Iodine-131 is more relevant in the immediate aftermath of a disaster, Cesium-137 and Strontium-90 contribute to extended environmental contamination, posing health risks for generations.

Table 2: Radioisotopes Involved with its Released Concentration

Nuclear Disaster	**Radioisotopes (PBq)**		
	Iodine-131	**Cesium-137**	**Strontium-90**
Kyshtym	NR	0.027	4
Windscale	1.8	0.18	0.075
Three Mile Island	74	NR	NR
Chernobyl	1760	85	10
Fukushima	120	8.8	NR

***Note:** NR indicates that the data is not reported in the available records. Some isotopes were released, but their exact concentrations were not specified.

Table 2 presents the released concentrations of Iodine-131, Cesium-137, and Strontium-90 from five major nuclear disasters: Kyshtym, Windscale, Three Mile Island, Chernobyl, and Fukushima. The values, measured in petabecquerels (PBq), indicate the extent of radioactive release, with some data was acknowledged but its exact concentration was not specified. The differences in isotope concentrations across these disasters highlight variations in accident severity, reactor design, and containment measures.

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Among these incidents, Chernobyl had the highest radioactive releases, with 1,760 PBq of Iodine-131, 85 PBq of Cesium-137, and 10 PBq of Strontium-90. These values far exceed those of other disasters, confirming Chernobyl as the most severe nuclear accident in terms of radioactive emissions. In comparison, Fukushima, the second-largest event in terms of releases, recorded 120 PBq of Iodine-131 and 8.8 PBq of Cesium-137, with no reported data for Strontium-90. The Iodine-131 release from Fukushima was only 6.8% of that from Chernobyl, and its Cesium-137 release was 10.4% of Chernobyl's, showing that while it was a major disaster, the total radioactive emissions were significantly lower.

Three Mile Island had a reported release of 74 PBq of Iodine-131 but no specified values for Cesium-137 or Strontium-90. Its Iodine-131 release was 4.2% of Chernobyl's and 61.7% of Fukushima's, making it a much smaller-scale event in terms of radioactive discharge. Windscale, another early nuclear accident, had even lower releases, with 1.8 PBq of Iodine-131, 0.18 PBq of Cesium-137, and 0.075 PBq of Strontium-90. Compared to Chernobyl, Windscale's Iodine-131 release was only 0.1%, and its Cesium-137 release was 0.2%, indicating its relatively minor impact in terms of radioactive contamination.

The Kyshtym disaster had no reported data for Iodine-131 but recorded 0.027 PBq of Cesium-137 and 4 PBq of Strontium-90. Although its overall radioactive release was much lower than that of Chernobyl, its Strontium-90 release was still 40% of the amount recorded at Chernobyl, making it notable for long-term environmental contamination. When comparing isotope releases across all disasters, Chernobyl had the most severe radioactive emissions, with Fukushima as the second-largest event but at significantly lower levels. Three Mile Island, Windscale, and Kyshtym had considerably lower releases, with some isotopes not reported, indicating limited contamination compared to the largest disasters.

D. Effects on Health and Environment

Radiation is associated with a wide range of adverse health outcomes when exposed (UCUSA, 2024). Exposure may be external (with or without contamination of skin, hair, clothes), internal (inhalation, ingestion or via a contaminated wound), or a combination of both (WHO, 2023).

Table 3: Health Effects of Nuclear Disaster

Nuclear Disaster	Health Effects
Kyshtym	Over 270,000 people were exposed to radiation, with more than 200 deaths from radiation sickness. Long-term effects included genetic disorders, cancer, leukemia, and birth defects.
Windscale	Increased thyroid cancer risk, particularly among children.
Three Mile Island	Minimal radiation exposure occurred. Studies found no significant health or environmental effects.
Chernobyl	134 workers suffered acute radiation sickness, leading to 28 deaths. Over 6,000 thyroid cancer cases were reported. Psychological effects such as stress, anxiety, and depression were widespread.
Fukushima	Estimated 130 (15–1100) to 180 (24–1800) cancer-related mortalities worldwide.

Table 3 shows the health effects resulting from five major nuclear disasters. Each disaster led to varying levels of radioactive exposure, and the extent of health impacts was influenced by factors such as the type and amount of released radioactive isotopes, population exposure, and long-term biological effects.

The Kyshtym disaster was one of the earliest major nuclear incidents, exposing over 270,000 people to radiation. More than 200 individuals died from acute radiation sickness, while long-term health effects included cancers, genetic disorders, and birth defects. The large population exposure suggests a significant radioactive release, although specific isotopic concentrations were not widely documented. Despite its severe consequences, Kyshtym is less recognized than later nuclear accidents, largely due to initial secrecy surrounding the event.

At Windscale, the primary concern was exposure to radioiodine, which accumulates in the thyroid gland and significantly increases the risk of thyroid cancer, particularly in children. This risk persists into adulthood, and long-term epidemiological studies in northwest England confirmed increased thyroid cancer cases among individuals born between 1929 and 1973 who were exposed to Windscale's radioactive fallout. Unlike Chernobyl, where multiple isotopes were released in large amounts, Windscale's primary health concern revolved around thyroid-related illnesses, and the overall scale of its impact was considerably smaller.

The Three Mile Island (TMI) accident resulted in a much lower radiation release compared to other disasters, and studies indicate that radiation exposure to the surrounding population was minimal. The average dose for two million residents was approximately 0.01 millisieverts, which is one-tenth of the radiation received during a routine transatlantic flight. The maximum site-boundary dose was 1 millisievert, a level still considered relatively low. While some debate exists regarding the long-term effects of the incident, comprehensive investigations concluded that TMI had negligible health consequences. Unlike Chernobyl and Fukushima, where thousands of people were displaced, TMI did not lead to widespread evacuations or long-term environmental contamination. The Chernobyl disaster had the most devastating health effects among all nuclear incidents. Immediately after the explosion, 134 workers developed acute radiation sickness, and 28 died shortly thereafter. Over time, more than 6,000 cases of thyroid cancer were reported, especially among children who were exposed to radioactive iodine. Leukemia and other forms of cancer have also been

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linked to the disaster, though some health impacts remain debated. Beyond physical health consequences, the psychological and social toll was significant—many affected individuals suffered from anxiety, depression, and social stigma, especially those forced to evacuate. By 2065, estimates suggest that Chernobyl-related radiation exposure could contribute to an additional 4,000 to 25,000 cancer-related deaths across Europe. These numbers make Chernobyl the deadliest nuclear accident in history in terms of human health impact.

The Fukushima disaster had a lower estimated health impact than Chernobyl but still contributed to radiation exposure among affected populations. Exposure pathways included inhalation, external radiation, and ingestion of contaminated food and water. Estimates indicate that Fukushima's radiation exposure could result in approximately 130 additional cancer-related fatalities in Japan, with a possible range of 15 to 1,100. On a global scale, projections suggest up to 180 additional deaths, with an estimated range between 24 and 1,800. Although these numbers are significantly lower than those associated with Chernobyl, they still represent a measurable public health impact. Unlike Chernobyl, where many acute radiation sickness cases occurred, Fukushima’s health concerns were more focused on long-term cancer risks and psychological stress from displacement and radiation fears.

Table 4: Long-Term Environmental Effects of Nuclear Disasters

Nuclear Disaster	**Long-Term Environmental Effects**
Kyshtym	River contamination, acid rain, and lasting radiation in farmland.
Windscale	Airborne release of I-131 and Cs-137, affecting livestock and dairy.
Three Mile Island	No significant contamination.
Chernobyl	Severe radiation effects on wildlife, forests, and water ecosystems.
Fukushima	Radioactive cesium detected in food and marine environments.

Table 4 provides an overview of the long-term environmental consequences of five major nuclear disasters. Each disaster had varying impacts on ecosystems, agriculture, water bodies, and wildlife, largely dependent on the extent of radioactive release, the isotopes involved, and the mitigation measures taken post-incident.

The Kyshtym disaster resulted in widespread environmental contamination due to the discharge of radioactive wastewater into a nearby river. This led to long-term pollution of the surrounding land and water sources, rendering agriculture hazardous. Acid rain caused by airborne radioactive chemicals further contributed to ecosystem damage, leading to the death of trees and plants. Given the high levels of radiation exposure, the land is expected to remain contaminated for centuries, with continued risks of genetic mutations and birth defects in both human and animal populations. In Windscale, radioactive materials, particularly iodine-131 (I-131) and cesium-137 (Cs-137), were dispersed across England, Wales, and parts of northern Europe. The estimated total release of I-131 was around 7,000 terabecquerels (TBq), with 1,800 TBq of reactive and particulate I-131 directly emitted into the atmosphere. A significant concern was the contamination of grass by I-131, which increased radiation exposure through the food chain, particularly in dairy products from cows grazing in affected areas. This type of environmental contamination posed long-term risks to human health through milk consumption, but the overall extent of contamination was lower than that seen in Chernobyl or Fukushima.

In contrast, Three Mile Island (TMI) had no significant long-term environmental contamination. The incident, while severe in terms of reactor damage, resulted in minimal radioactive release, and extensive studies found no lasting impact on ecosystems, agriculture, or human settlements. TMI serves as an example of how containment measures and reactor design played a role in mitigating environmental consequences despite a nuclear accident occurring.

The Chernobyl disaster had the most catastrophic long-term environmental consequences of all nuclear accidents. Extensive radiation release caused increased mortality and reproductive issues in plant and animal populations. Many forests, water bodies, and freshwater ecosystems experienced prolonged contamination. Although the exclusion zone became a unique wildlife refuge due to human absence, scientists observed genetic mutations and a decline in bird species exposed to high radiation levels. While some species adapted, concerns about ecological imbalances persist. The scale and duration of Chernobyl's environmental impact remain unparalleled, with radiation expected to affect ecosystems for thousands of years. Moreover, The Fukushima disaster primarily affected coastal and agricultural environments due to the release of radioactive cesium. Contaminated soil, water, and food sources, such as mushrooms, wild plants, boar meat, and fish, were recorded with high radiation doses. In particular, cesium was detected in preserved food and seafood from coastal waters near the Fukushima Daiichi Nuclear Power Plant. While some mitigation efforts, including decontamination, have reduced radiation levels in the environment, persistent contamination in specific food sources and ecosystems continues to raise concerns. The long-term effects are still being studied, but Fukushima’s environmental impact, while severe, is not as extensive as Chernobyl’s due to lower radiation release and containment efforts.

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E. Decontamination

Table 5: Decontamination and the Actions Taken of Nuclear Disasters

Nuclear Disaster	Decontamination Methods	Key Actions Taken
Kyshtym (1957)	Land remediation, waste containment, controlled exposure for cleanup workers	Isolated contaminated zones, monitored radiation exposure, used military and civilian personnel for cleanup
Windscale (1957)	Top-down reactor dismantling, robotic fuel removal, graphite core handling	Removed contaminated reactor components, applied safety shielding measures
Three Mile Island (1979)	Water flushing, detergent cleaning, strippable coatings, ion-exchange resin for liquid waste	Decontaminated reactor surfaces, removed fuel debris, filtered radioactive water
Chernobyl (1986)	Soil removal, vacuuming, mechanical decontamination, concrete shielding, robotic cleanup	Removed contaminated soil, used bioshielded machinery, created an exclusion zone
Fukushima (2011)	Incineration, ash washing, cesium adsorption using Prussian blue, controlled landfill disposal	Removed radioactive cesium from food and water, decontaminated soil, stored radioactive material safely

The decontamination efforts following major nuclear disasters varied significantly, depending on the extent of radioactive contamination, the isotopes involved, and the environmental conditions. Each disaster required a different approach to minimize radiation exposure, mitigate ecological damage, and ensure public safety. The complexity of these cleanup operations was influenced by the severity of radioactive release, the affected geography, and the technological capabilities available at the time of each incident.

The Chernobyl disaster required the most extensive and prolonged decontamination efforts due to the widespread release of radioactive isotopes, particularly cesium-137 and strontium-90. Immediately after the explosion, efforts focused on stabilizing the site by covering the damaged reactor with a temporary concrete sarcophagus to contain radiation. However, significant radioactive materials had already spread across large areas, contaminating forests, water bodies, and agricultural land.

In response, Soviet authorities established a 30-kilometer exclusion zone, relocating over 100,000 residents to prevent further exposure. Cleanup crews removed large amounts of contaminated soil, vacuumed radioactive dust, and applied concrete shielding to critical areas. Robotic systems were deployed to remove highly radioactive debris, although many malfunctioned due to extreme radiation levels. Eventually, a more permanent solution, the New Safe Confinement, was constructed over Reactor 4 to provide long-term containment (Yurchenko, 2021). Despite these efforts, radiation remains a concern in the surrounding environment, with wildlife and plant life showing signs of mutation and bioaccumulation of radioactive elements.

The Fukushima disaster, though less severe than Chernobyl in terms of radiation release, required extensive decontamination efforts due to contamination of water, soil, and food sources. A major concern was the release of cesium-137, which contaminated agricultural products, marine life, and groundwater. Decontamination strategies included incineration of contaminated plant material, followed by washing the resulting ash to extract radioactive cesium. Additionally, cesium adsorption materials like Prussian blue were used to remove radioactive contaminants from water sources before safe storage. Soil remediation involved scraping off surface layers and applying potassium-based fertilizers to limit cesium absorption by crops. To address water contamination, specialized filtration systems, such as Advanced Liquid Processing Systems (ALPS), were deployed to remove radioactive isotopes from cooling water before controlled release into the ocean (Parajuli, 2013).

Since the Three Mile Island accident primarily resulted in a partial reactor meltdown with limited environmental contamination, decontamination efforts focused on reactor cleaning and waste management. The primary methods used included water flushing and detergent-based cleaning to remove radioactive contamination from surfaces. Strippable coatings were applied to exposed areas and later peeled off to safely remove radioactive residues. Additionally, ion-exchange resins were used to filter radioactive particles from contaminated cooling water, preventing further spread of radiation. The cleanup process took over a decade, but ultimately, Three Mile Island's decontamination was more manageable due to its confined nature, and environmental impacts were minimal compared to other nuclear disasters (World Nuclear Association, 2022).

The Windscale fire, which released airborne radioactive materials, particularly iodine-131 and cesium-137, required unique decontamination approaches. Since much of the contamination affected the atmosphere and surrounding grasslands, the primary concern was preventing radioactive exposure through food and air. Initially, containment measures included sealing the damaged reactor and installing filtered ventilation systems to prevent further radioactive emissions. Contaminated areas inside the reactor were covered with concrete, while robotic arms were later deployed to remove fuel debris from the graphite core. The reactor remained sealed for decades due to high radiation levels, and when decommissioning efforts finally began, a top-down dismantling approach was used. This process involved robotic removal of the graphite core and surrounding structures, allowing for safer dismantling while minimizing radiation exposure (Sexton, 2007).

The Kyshtym disaster, caused by the explosion of a high-level radioactive waste storage tank, led to severe contamination of surrounding land and water. Unlike reactor-based accidents, Kyshtym's primary challenge was the uncontrolled release of radioactive materials into the environment, particularly in the form of radioactive plumes and liquid contamination. Decontamination efforts focused on land remediation and containment to limit further spread. Thousands of military and civilian workers were deployed for cleanup operations, with strict radiation exposure limits enforced to protect personnel. Contaminated areas were evacuated, and long-term radiation monitoring was implemented to track exposure levels (Vasilenko et. al, 2020). Although the cleanup helped stabilize the situation, the region remained contaminated for decades, with residual radiation still detectable in some areas.

IV. CONCLUSION

This systematic review underscores the significant and far-reaching consequences of major nuclear disasters on human health, the environment, and energy policies. Among the incidents analyzed, the Chernobyl disaster proved to be the most severe in terms of radiation release, health effects, and environmental contamination, with its long-term consequences persisting to this day. The Fukushima disaster, while releasing significantly less radiation, demonstrated the extensive socio-economic and psychological impacts of nuclear accidents, particularly in relation to public displacement and mental health. The Three Mile Island incident, though resulting in minimal radioactive exposure, highlighted the influence of nuclear accidents on public perception and policy changes. Meanwhile, the Kyshtym and Windscale disasters, occurring in the earlier years of nuclear development, illustrate the risks associated with inadequate safety measures and technological limitations at the time.

A key finding of this review is that nuclear disasters arise not only from technical malfunctions but also from human errors, insufficient regulatory oversight, and, in certain cases, natural disasters. The varied decontamination efforts undertaken across these events highlight the challenges of mitigating radioactive contamination, with strategies ranging from soil removal and reactor entombment to long-term environmental monitoring. While some affected regions remain uninhabitable, ongoing remediation efforts, particularly in Fukushima, continue to address contamination concerns.

The findings of this review emphasize the critical need for enhanced nuclear safety regulations, improved reactor designs, and more effective emergency response protocols to minimize the risks associated with nuclear energy. Furthermore, transparent communication and public awareness initiatives are essential in addressing misinformation and fostering informed discussions on nuclear energy policies. While nuclear power remains a significant energy source, its safe utilization requires rigorous oversight, continuous advancements in safety technology, and a commitment to preventing future nuclear disasters.

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