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*CORRESPONDENCE
Chee Kong Yap
✉ yapchee@upm.edu.my

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Chernobyl nuclear catastrophe: lessons for sustainability and UNSDGs in health, energy, and environmental recovery

Chee Kong Yap[1]* and Khalid Awadh Al-Mutairi[2]

[1]Department of Biology, Faculty of Science, Universiti Putra Malaysia, Selangor, Malaysia, [2]Department of Biology, Faculty of Science, University of Tabuk, Tabuk, Saudi Arabia

This study provides a comprehensive review of the research surrounding the Chernobyl nuclear incident, focusing on its far-reaching impacts on human health, and environmental contamination. Based on the Scopus database, 258 relevant papers were identified using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. These papers were metal-analyzed and quantitatively analyzed using a similarity map generated through VOSViewer in order to visualize key themes and their interconnections. The research highlights critical areas such as radiation-induced health effects, ecological damage, and the implications for sustainable energy practices. Additionally, this review explores the alignment of these findings with several United Nations Sustainable Development Goals (UNSDGs), particularly UNSDG 3 (Good Health and Wellbeing), UNSDG 6 (Clean Water and Sanitation), UNSDG 7 (Affordable and Clean Energy), UNSDG 13 (Climate Action), and UNSDG 15 (Life on Land). By synthesizing existing research, this study emphasizes the importance of integrating safety protocols, environmental rehabilitation, and sustainable energy policies to prevent and to mitigate the impacts of future nuclear incidents.

KEYWORDS

Chernobyl, nuclear contamination, radiation health, environmental implications, sustainability

1 Introduction

The year 1986 is marked by two significant global events: the Mexico FIFA World Cup and the Chernobyl Nuclear Disaster (CND). The analysis of public attention toward these events prompts an inquiry into which incident achieved greater global awareness and impact. From a socio-environmental perspective, the 1986 CND was prominently reported in local and international newspapers, as well as in reports from the International Atomic Energy Agency (IAEA), including forums and conferences, and in academic literature. Numerous reports indicate that the CND is regarded as one of the most catastrophic technological and environmental incidents in human history. This analysis considers the persistent significant impacts on human health, ecological redistribution, and global energy policies (1–4). The failure of Reactor No. 4 at the Chernobyl Nuclear Power Plant released significant amounts of radioactive materials into the atmosphere. This has led to significant contamination across various European nations, including Ukraine, Russia, and Belarus (5–7). The immediate health effects, including acute radiation syndrome and the mandatory evacuation of over 300,000 people, initiated a prolonged global response to this unprecedented nuclear disaster (8–10). Recent studies demonstrate the lasting impacts of the catastrophe on human health, the environment, and energy security, underscoring its significance in comprehending the risks associated with nuclear power (11–13).

The CND provides important insights relevant to the objectives set by the United Nations Sustainable Development Goals (UNSDGs) (14). Nuclear power is a contentious option in the global transition to clean energy for mitigating climate change, largely because of the potential for catastrophic events, as illustrated by CND (15). Secure, low-carbon energy sources are crucial; however, the CND disaster underlines the importance of stringent safety standards and preparedness for emergencies within the energy sector (16). The CND stresses the necessity of balancing energy efficiency with environmental safety in climate change initiatives (17). The health effects of Chernobyl have been the subject of extensive research. The CND resulted in a rise in cases of radiation-54-related malignancies, thyroid disorders, psychological distress, and possible genetic anomalies, thereby raising substantial public health concerns (18).

The CND had a disproportionate impact on children and pregnant women, resulting in long-term psychological trauma for survivors, which requires continued epidemiological research and healthcare support (18–20). The environmental consequences were significant, affecting soil, water, and ecosystems, with detrimental impacts on biodiversity and food security, necessitating restoration and mitigation efforts (21). The exclusion zone has emerged as an ecological research site, illustrating nature's resilience in the face of ongoing contamination (22). The disaster underscored the necessity for institutional and policy reforms, highlighting the significance of transparent governance, crisis management, and international cooperation in mitigating nuclear risks (23, 24). The Soviet government's inability to deliver timely information and effectively manage the crisis exacerbated its consequences, highlighting the importance of robust institutions, international dialogue, and revised nuclear safety regulations to avert future disasters (25, 26).

Extensive research over the decades has examined the environmental, health, and remediation aspects of the CND. The IAEA (27) conducted an initial evaluation via The International Chernobyl Project, detailing both the immediate and long-term consequences of the accident. Ten years later, a detailed summary of the outcomes was recorded, highlighting the socio-economic and health effects of radiation exposure (28). Subsequent analysis examined the environmental consequences of the disaster, outlining remediation strategies and insights gained over two decades (29). IAEA (30) highlighted the significance of historical lessons in informing future nuclear safety policies. In 2019, the IAEA evaluated the environmental effects of the cooling pond drawdown at the Chernobyl Nuclear Power Plant, aiding in the ongoing decommissioning and ecological recovery efforts. These studies collectively underscore the importance of ongoing monitoring, remediation, and policy development to address the long-term effects of CND.

This review acknowledges the incorporation of references from IAEA reports regarding the CND. The current study is based on a thorough review of peer-reviewed literature indexed in Scopus, which ensures rigorous academic scrutiny and broad scientific consensus. The incorporation of IAEA reports, which mainly reflect institutional viewpoints, may result in a bias that contrasts with independent research outcomes recorded in Scopus database studies. The Scopus database includes numerous independent research articles that analyze the long-term health, environmental, and socio-economic impacts of the CND, facilitating a diverse and nuanced discussion. IAEA reports serve as important official documentation; however, their institutional perspective frequently prioritizes regulatory and policy interpretations over independent empirical research. This review paper includes a brief mention of significant IAEA reports to acknowledge their perspective, while prioritizing peer-reviewed empirical research sourced from the Scopus database to maintain academic integrity.

This review paper aims to assess insights gained from the CND and evaluate their significance in relation to the UNSDGs, utilizing the Scopus database. This review aims to clarify the important connections between nuclear safety, environmental resilience, and sustainable development by analyzing the long-term impacts of the CND on public health, environmental management, and global governance.

2 Methodology

This research utilized a bibliometric analysis to examine the scientific literature concerning the CND. Bibliometric analysis serves as a quantitative approach for evaluating the influence and development of scientific research through the examination of publication and citation trends (31). This methodology sought to delineate the scope and principal trends in research pertaining to Chernobyl, as recorded in the Scopus database during the period from 1986 to 2024.

This review utilized the Systematic Literature Review methodology in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines established by Moher et al. (32) to enhance understanding of the "Chernobyl Disaster." PRISMA offers a framework grounded in evidence to promote transparency and facilitate critical evaluation in research. Figure 1 illustrates the formal steps adapted for this study. Scopus was selected as the primary database because of its extensive and multidisciplinary coverage of high-quality, peer-reviewed content, establishing it as a reliable resource for academic research (33). A keyword search for "Chernobyl Disaster" was performed in Scopus, encompassing publications from 1986 to October 10, 2024. Only abstracts containing relevant keywords and addressing significant issues were included. The initial selection aimed to minimize bias by focussing exclusively on paper titles that included the specified keywords, without considering authors' names or countries of origin. This approach facilitated an objective and systematic selection of literature for analysis.

A total of 258 papers have been included for quantitative synthesis (meta-analysis) and will be analyzed using VOSViewer (version 1.6.20; 2009–2023 Van Eck & Waltman; Leiden University, The Netherlands). The metadata was imported into VOSviewer, a software specifically developed for constructing and visualizing bibliometric networks (31). VOSviewer was employed to manage extensive datasets and illustrate intricate relationships among terms in the literature. The software constructs a network utilizing the frequency of term co-occurrence in the chosen publications. Co-occurring terms were often linked by edges, with

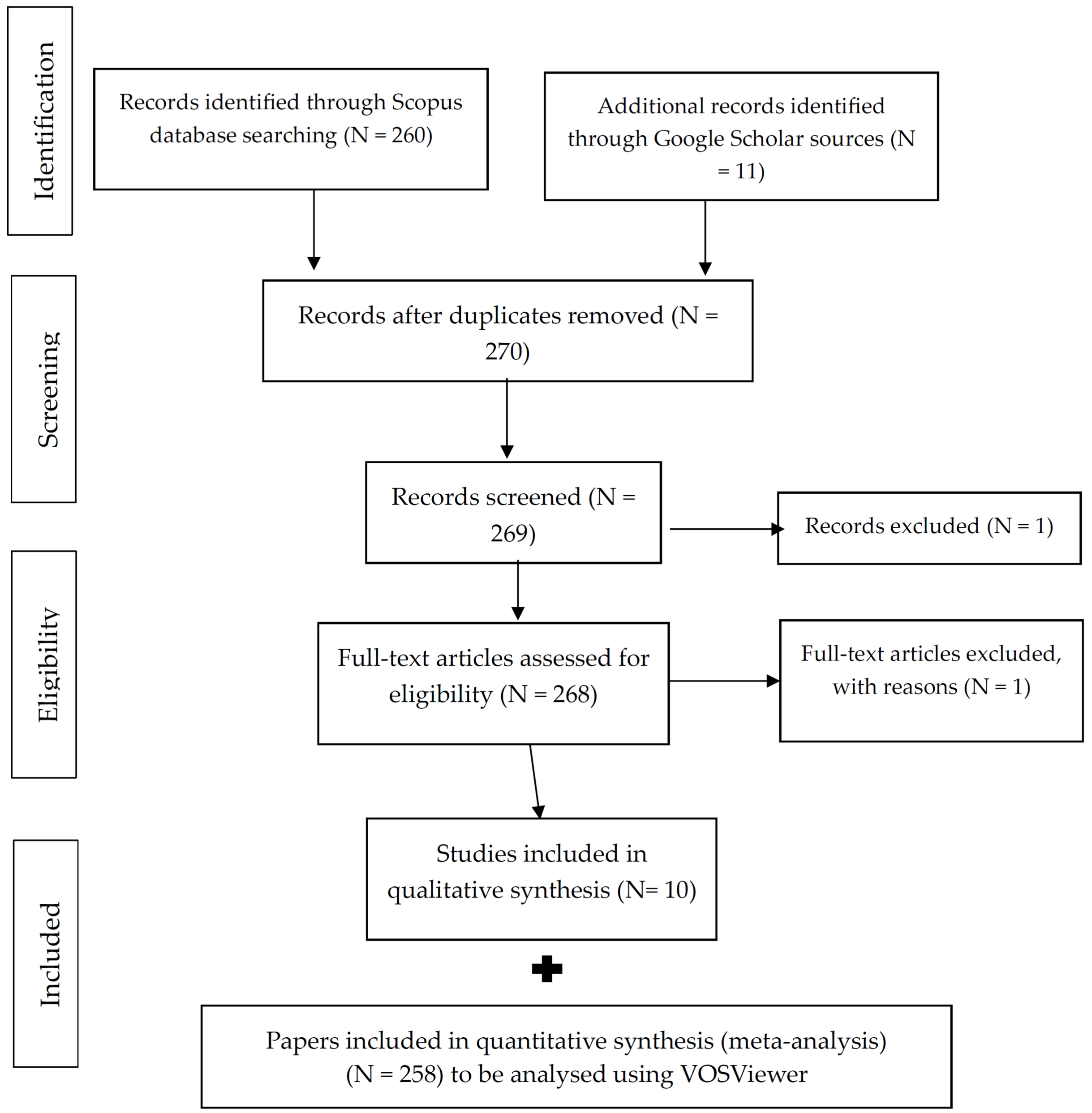

FIGURE 1
Flowchart of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [adapted from Moher et al. (32)], used in the present study.

the strength of these connections indicating the level of co-occurrence (34).

VOSviewer subsequently employed its clustering algorithm to categorize related terms into distinct clusters. Each cluster represented a distinct research theme or topic, with clusters color-coded for enhanced interpretation. This visualization method facilitated a clear comprehension of the primary research domains and their relationships (35). The identified clusters revealed important research topics and their interconnections, emphasizing emerging trends in the investigation of the CND (31, 34, 36).

The clustering analysis facilitates the mapping of research themes related to the UNSDGs, specifically in the areas of health, environmental sustainability, and energy policy. The mapping of thematic clusters highlighted the significance of Chernobyl-related research in relation to global sustainability and planetary health issues.

3 Results and discussion

The Scopus database found 258 papers. This study's results (Figure 2) illustrate the co-occurrence and interconnections among academic keywords related to the Chernobyl Disaster. Each node represents a keyword or concept, and the links between nodes indicate the strength of their association based on co-occurrence in academic literature.

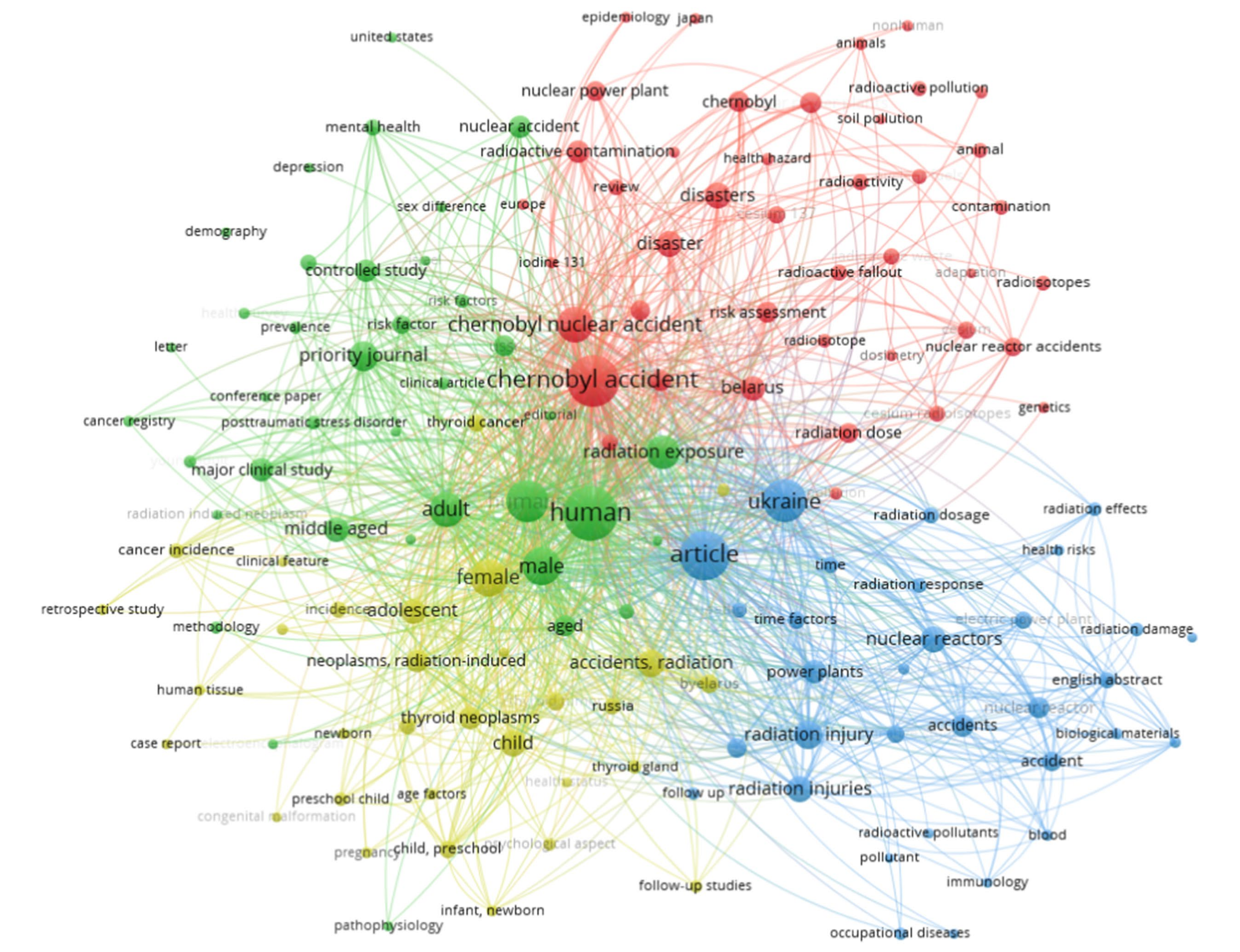

FIGURE 2
Visualization of similarity using VOSviewer based on 258 publications indexed in the Scopus database from 1986 to 2024 using the keyword "Chernobyl Disaster" searched on 10 October 2024.

The network visualization of the CND reveals four distinct clusters representing the main thematic areas of study related to this disaster (Figure 2). The clusters, identified by color, provide insights into the breadth of research topics and their interconnections. Each cluster is characterized by its own major keywords that shed light on the various facets of the CND and its aftermath.

3.1 Clustering interpretations

The network visualization of research related to the CND reveals four primary areas of focus, each characterized by a unique emphasis. This analysis will examine the implications of the research findings for each cluster and investigate the interrelationships among them.

3.1.1 Red cluster: emphasis on environmental and geopolitical issues

The red cluster, focused on radioactive pollution and nuclear accidents, underscores the significant environmental and geopolitical consequences of the CND (37–39). Research on nuclear power plants and radioactive fallout analyses the immediate and long-term environmental impacts of disasters, particularly regarding soil, water, and air pollution (40–42). The distribution of radioisotopes such as iodine-131, cesium-137, and strontium-90 is crucial for evaluating the extent of environmental degradation (43, 44). The ongoing presence of these radionuclides in the environment highlights the seriousness of contamination, particularly in agricultural regions, where radioactive soil pollution has direct implications for food safety and human health (45, 46).

The geopolitical aspect of this cluster is underscored by mentions of Belarus, Ukraine, and nuclear reactor incidents, reflecting the regional focus of the majority of the research (47, 48). Ukraine and Belarus, the two nations most affected by the aftermath, have been the subject of numerous studies analyzing the accident's social, political, and economic consequences (49, 50). Research indicates that nuclear disasters like Chernobyl place significant demands on governments, involving both immediate crisis response and long-term recovery efforts (51, 52). Radiation exposure levels in these nations pose a significant concern, impacting public health as well as agricultural and economic activities, given that extensive areas have remained polluted and uninhabitable for decades (53). The focus on radioactive and soil pollution underscores the ongoing challenges in mitigating environmental damage, indicating the need for ongoing monitoring and remediation efforts (54–56).

The findings have significant implications for international nuclear energy policy, influencing discussions regarding the safety of nuclear power as a viable energy source in the context of climate change mitigation (37). CND serves as a case study for evaluating global nuclear reactor readiness, emphasizing the critical needs for safety protocols, emergency responses, and international cooperation in the event of future nuclear incidents (20, 38).

3.1.2 Green cluster: human health and epidemiology

The green cluster examines the human health effects of the Chernobyl accident, with an emphasis on epidemiological analysis (39, 57). Demographic effects of radiation exposure have been extensively studied, particularly concerning vulnerable groups such as females, males, children, adolescents, and infants (47, 48). Thyroid cancer, radiation-induced neoplasms, and post-traumatic stress disorder illustrate the significant medical and psychological effects on populations exposed to radiation. Thyroid cancer is notably one of the most well-documented health outcomes, especially in children and adolescents exposed to iodine-131 fallout (49, 50).

Research on cancer incidence and risk factors has shown a significant rise in radiation-induced malignancies, impacting thyroid tissues as well as various other organs (51, 52). Research indicates that children and adolescents exhibit heightened susceptibility to thyroid neoplasms due to the accumulation of radioactive iodine in the thyroid gland, primarily from contaminated milk and other dietary sources (53, 56). The terms prevalence and clinical aspects suggest that the study primarily aims to clarify the unique features of these malignancies, their latency periods, and the probability of recovery with early detection (55).

The psychological impact of the disaster has been considerable, as evidenced by the focus on mental health, and depression (54). Survivors, particularly those who have experienced displacement or high radiation exposure, exhibit persistent mental health challenges (20, 37). This research emphasizes the need for comprehensive mental health services for Chernobyl survivors, many of whom continue to face trauma related to displacement, loss, and ongoing health issues (38, 41). This cluster emphasizes the demographics and health conditions of communities exposed to radiation, suggesting that comprehensive epidemiological investigations are crucial for understanding the broader public health implications of nuclear disasters (40, 42).

This cluster presents concerning implications for reproductive health, as indicated by terms such as pregnancy, congenital abnormalities, and infants (43, 44). Research in this field has shown that radiation exposure can lead to increased rates of congenital anomalies and developmental impairments, affecting future generations in regions exposed to radiation fallout (46). The findings highlight the intergenerational health effects of the Chernobyl disaster, underscoring the need for extended health monitoring and support for the impacted communities (45).

3.1.3 Blue cluster: radiological harm and technical investigations

The blue cluster presents a technical perspective, emphasizing radiation injuries, nuclear reactors, and radiation dosage (47, 48). This research aims to clarify the mechanisms of radiation damage and to develop criteria for measuring radiation exposure in both acute and chronic contexts (49, 50). Terms like radiation dose, radiation response, and radiation damage suggest that a considerable focus of this research is on dosimetry, which involves the quantification and assessment of the radiation dose absorbed by individuals, as well as the biological reactions to varying radiation levels (51, 52).

The terms nuclear reactors, radiation impacts, and accident pertain to research that investigates the technical aspects of nuclear power generation and the deficiencies that led to the Chernobyl disaster (53, 56). Investigations are crucial for identifying vulnerabilities in nuclear power plant operations, leading to legislative and engineering changes to prevent future accidents (55). Research on power plants and electrical systems has improved understanding of the mechanisms underlying nuclear disasters, highlighting aspects such as reactor design, maintenance, and violations of safety protocols (54).

This cluster's focus on radiation injuries and biological materials indicates that research has also addressed the medical and biological consequences of radiation exposure (37, 39). Radiation injuries range from acute radiation sickness (ARS) to long-term health effects, including cancer and organ damage (38). This study investigates the physiological mechanisms underlying these injuries, focussing on the damage caused to DNA and cells due to increased radiation exposure (41, 42). The classification of occupational illnesses highlights the risks faced by workers in nuclear facilities, as exposure to radiation in the workplace has been linked to long-term health problems (40, 43).

Additionally, the terms health hazards and dosimetry suggest that researchers are improving the tools and models used to predict the effects of radiation exposure (44, 46). Accurate measurement of radiation exposure is crucial for public health and safety, enabling suitable medical interventions and minimizing long-term health risks for populations exposed to radiation (45).

3.1.4 Yellow cluster: pediatric and long-term health implications

The yellow cluster highlights the enduring health effects of the CND, particularly for children and vulnerable populations (47, 48). The terms child, adolescent, newborn, and baby pertain to pediatric research, examining the health impacts of radiation exposure on younger populations (49, 50). Research demonstrates that children exposed to radiation have an increased risk of cancer, particularly thyroid neoplasms, due to the accumulation of radioactive iodine in their thyroid glands (51, 52).

Extended studies on cancer incidence, congenital anomalies, and radiation-induced malignancies reveal a troubling trend in the health outcomes of children exposed to radiation (53, 56). Including terminology such as retrospective research, follow-up studies, and risk variables stresses the necessity for ongoing surveillance of these populations, since the comprehensive consequences of radiation exposure may take decades to become apparent (54, 55). This has led to comprehensive research on the latency period for cancer progression and other chronic health conditions (37, 58).

Congenital abnormalities, pregnancy, and newborn status reflect concerns regarding the impact of radiation exposure on reproductive health and fetal development (38, 41). Studies indicate increased rates of congenital anomalies and developmental impairments in children of parents exposed to radiation (40, 42). The findings have important implications for public health, suggesting that the effects of radiation exposure may persist across multiple generations. This cluster highlights the importance of methodology and pathophysiology, advocating for research into the biological mechanisms that affect health outcomes to improve diagnostic and treatment strategies for impacted populations (43, 44).

The research on the CND is extensive, covering environmental, health, technological, and long-term pediatric dimensions. The network visualization demonstrates the interconnections among these issues, reflecting the complexity of the disaster's impacts on human health, the environment, and nuclear safety regulations (45, 46). Each cluster offers significant insights into various facets of the catastrophe, highlighting the necessity for ongoing investigation and surveillance to comprehensively comprehend and alleviate the enduring repercussions of the CND (47, 48).

3.2 Relation to the UNSDGs

The examination of the CND is highly relevant to numerous UNSDGs. The incident has significant implications for human health, the environment, energy policy, economic sustainability, and international collaboration, in accordance with the primary objectives of the UNSDGs (49, 50). This discussion addresses the pertinent UNSDGs related to the CND (Figure 3).

3.2.1 UNSDG 3: good health and wellbeing

The health consequences of the CND, both immediate and long-term, are directly associated with UNSDG 3, which aims to ensure healthy lifestyles and improve wellbeing for individuals across all age groups (51, 52). The network visualization depicts clusters of research related to radiation-induced malignancies, thyroid neoplasms, and radiation injuries, all demonstrating the direct impact of nuclear accidents on public health (53, 56). Studies on thyroid cancer, mental health, post-traumatic stress disorder, and congenital malformations highlight the considerable effects of radiation exposure on individuals, especially within vulnerable populations such as children, women, and the older adult (54, 55).

The focus on long-term health monitoring, indicated by terms like follow-up research, retrospective study, and cancer incidence, suggests that sustaining good health and wellbeing requires continuous healthcare support for affected communities (37, 59). This emphasizes the necessity of investing in preventive healthcare initiatives and disaster preparedness to mitigate the long-term health effects of radiation exposure in potential future nuclear incidents (38, 41). Research on mental health disorders following disasters highlights the importance of psychological care and rehabilitation, especially for displaced populations, in alignment with UNSDG 3's goal of addressing both physical and mental wellbeing (40, 42).

3.2.2 UNSDG 6: clean water and sanitation

UNSDG 6 highlights the importance of clean water and sanitation, particularly in relation to the CND, due to the environmental pollution affecting water supplies (43, 44). The red cluster in the network visualization indicates radioactive contamination, soil pollution, and radioactive fallout, demonstrating that nuclear disasters pose a significant threat to the safety of water systems (45, 46). Following the CND, radioactive isotopes, including cesium-137 and iodine-131, impacted vast areas, notably water resources. This pollution negatively affects human populations and damages

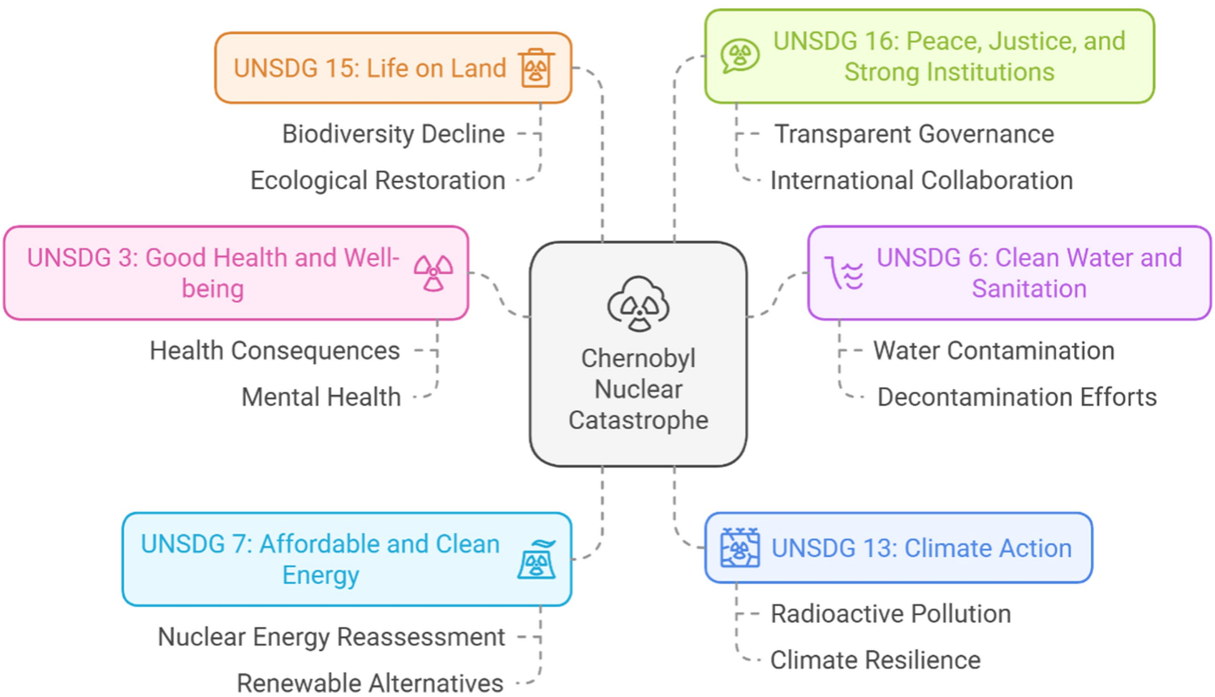

FIGURE 3
Overall relationships of Chernobyl nuclear disaster with United Nations' Sustainable Development Goals, based on the present literature review.

ecosystems, threatening food and water security in the impacted regions (47, 48).

The pollution of natural water bodies and the subsequent leaching of radioactive substances into groundwater threaten the achievement of UNSDG 6, which aims to ensure the availability and sustainable management of water for all (49, 50). Research on soil contamination and radioactive deposition demonstrates that decontamination and ecological restoration are essential for restoring safe water sources in regions impacted by nuclear disasters (51, 52). It is crucial to implement sustainable water management systems that account for potential environmental disasters to avert future occurrences (53, 56).

3.2.3 UNSDG 7: affordable and clean energy

UNSDG 7 promotes access to affordable, reliable, sustainable, and modern energy sources. The CND had a substantial impact on global energy policy, particularly regarding the safety and sustainability of nuclear power (54, 55). The blue cluster in the network visualization emphasizes terms such as nuclear reactors, nuclear disasters, and power plants, reflecting the technical assessments and discourse surrounding the safety of nuclear energy (37, 58).

The CND underscores the risks associated with nuclear energy, prompting a reevaluation of its role in achieving clean energy goals (38, 41). Many countries re-evaluated their reliance on nuclear energy, choosing instead to pursue alternative renewable energy sources like solar and wind (40, 42). Nuclear energy is often considered a low-carbon energy source; however, it poses significant safety risks. The case of CND illustrates that the environmental and health impacts can greatly outweigh the benefits if safety protocols are not strictly enforced (43, 44). UNSDG 7 emphasizes that the provision of clean and affordable energy requires rigorous safety protocols and disaster preparedness to prevent nuclear incidents and reduce their impact on people and the environment (45, 46).

3.2.4 UNSDG 13: climate action

UNSDG 13 requires prompt actions to tackle climate change and its effects. The CND highlights the environmental risks associated with nuclear power generation, which is viewed by some as a strategy to reduce greenhouse gas emissions (47, 48). The red cluster, which includes terms like radioactive pollution, radioactive fallout, and nuclear reactor accidents, underscores the paradox of nuclear energy: it offers a low-carbon alternative to fossil fuels while posing significant environmental risks in the event of accidents (49, 50).

The radioactive contamination of large areas in Ukraine, Belarus, and Russia has rendered these regions unsuitable for agriculture and human settlement, leading to challenges in land use and environmental restoration (51, 52). Addressing the climate change challenge requires a nuanced energy policy that considers the potential risks of nuclear energy in relation to its low-carbon benefits. Achieving UNSDG 13 requires the advancement of clean energy and the guarantee that energy systems are resilient to incidents and disasters, exemplified by the events at Chernobyl (53, 56).

3.2.5 UNSDG 15: life on land

The red and yellow clusters illustrate the significant environmental and ecological damage caused by the CND, directly correlating with UNSDG 15, which focusses on the protection, restoration, and sustainable use of terrestrial ecosystems (54, 55). The catastrophe resulted in significant radioactive contamination, as evidenced by the concepts of radioactive pollution, radioactive fallout, and contamination. The contaminants adversely affected the nearby soil, vegetation, and wildlife, leading to substantial alterations in ecosystems and a decline in biodiversity in the affected regions (37, 59).

Studies on soil contamination and radiation-induced changes in ecosystems demonstrate that extended remediation of these environments is essential for achieving Life on Land (38, 41). Contaminated areas like the Chernobyl Exclusion Zone continue to exhibit altered biological dynamics, characterized by the extinction of some species and the proliferation of others, such as wolves and wild boars, due to the absence of human activity (40, 42). Achieving UNSDG 15 requires ongoing efforts to monitor and rehabilitate ecosystems to restore biodiversity and mitigate the persistent environmental damage caused by radioactive pollution (43, 44).

3.2.6 UNSDG 16: peace, justice, and strong institutions

UNSDG 16 emphasizes the promotion of peaceful and inclusive societies, equitable justice access, and strong institutions. The CND, particularly in relation to the geopolitical aspects of the red cluster (e.g., Belarus, Ukraine, disasters, and radioactive contamination), illustrates the importance of transparent governance, international cooperation, and effective institutional responses to crises (45, 46). The catastrophe exposed significant shortcomings in official response systems, particularly in the Soviet Union, where initial concealment of information exacerbated the public health crisis and delayed foreign aid (47, 48).

To ensure peace, justice, and strong institutions in the context of nuclear disasters, governments must adopt transparent policies, maintain open communication with the public, and collaborate with international organizations (49, 50). The CND emphasized the importance of risk assessment, radiation monitoring, and effective emergency response systems in preventing fatalities and mitigating environmental damage (51, 52). Establishing strong institutions that can effectively manage nuclear safety, environmental conservation, and public health is essential for preventing future disasters of similar scale (53, 56).

The legacy of the CND offers important insights into various dimensions of sustainability, encompassing health and environmental restoration, institutional governance, and energy policy. The ongoing relevance of the catastrophe in discussions regarding the UNSDGs highlights the continued need to understand and address the long-term effects of nuclear accidents (54, 55). The lessons from Chernobyl will be crucial in achieving a balance among energy security, environmental stewardship, and human welfare as the world progresses toward a sustainable future (37, 59).

3.3 Synthesis and future challenges

The CND serves as a critical example of the substantial environmental, health, and socio-political consequences of industrial accidents (23, 25). The legacy of Chernobyl is highly relevant to multiple UNSDGs, even though these goals were established decades later. The impact of the disaster on public health aligns with the goals of UNSDG 3 (Good Health and Wellbeing), emphasizing the need for ongoing health monitoring and comprehensive healthcare interventions, particularly regarding radiation-related illnesses (26, 60). The pollution of aquatic environments and ecosystems highlights the urgent need for UNSDG 6 (Clean Water and Sanitation) and UNSDG 15 (Life on Land), which underscore the significance of sustainable resource management and ecosystem restoration (50, 52). The impact of Chernobyl on global energy discourse is fundamentally associated with UNSDG 7 (Affordable and Clean Energy), which promotes the equilibrium between energy needs and safety (24, 61).

The paradox of ecosystem recovery in the exclusion zone, where wildlife has flourished in the absence of human interference despite radiation, underscores complex insights regarding UNSDG 13 (Climate Action) and ecosystem resilience (13, 62). The unintentional restoration of the region demonstrates nature's ability to recover without human intervention; however, the persistent radiation highlights the long-lasting and intricate consequences of industrial disasters (58, 63). UNSDG 17 (Partnerships for the Goals) is relevant to the global response and cooperation necessary to mitigate the effects of Chernobyl. The catastrophe prompted global efforts to improve nuclear safety protocols and foster international collaboration, a crucial consideration for the internationalization of the UNSDGs (53, 56).

3.4 Prospective challenges and dilemmas

This analysis provides a comprehensive examination of these impacts based on the available references (Figure 4).

3.4.1 Equilibrating nuclear energy and safety

Nuclear power continues to be a debated alternative in the pursuit of low-carbon energy solutions (51, 64). The CND underlined the significant risks linked to nuclear energy, prompting numerous countries to decrease or abandon their dependence on it. Nuclear energy remains essential as a low-emission energy source in light of the pressing need to combat climate change (52, 65). The challenge involves reconciling the need for clean energy with the associated risks of CND. Advancements in nuclear technology, including next-generation reactors equipped with passive safety systems, are essential for risk mitigation; however, they necessitate substantial investment and international collaboration (57, 66). This prompts a discussion regarding the prioritization of rapid advancements in renewable energy technologies versus nuclear power, taking into account the relevant trade-offs.

The CND significantly influenced the global nuclear industry, diminishing public trust in nuclear energy and leading to an international re-evaluation of safety protocols (67). Some countries reduced their dependence on nuclear power, whereas others, such as Russia, continued to expand their nuclear capabilities with improved safety protocols (68). The disaster prompted advancements in reactor design and the establishment of enhanced safety frameworks globally (69).

3.4.2 Socio-economic impact

The CND had significant socio-economic impacts, affecting around 350,000 evacuees and placing considerable pressure on the social and economic frameworks of the impacted areas (70). Ukraine allocates 5–7% of its annual government budget to address the long-term consequences of the disaster, indicating a persistent financial burden (71). Significant economic losses resulting from compensation, healthcare, and cleanup initiatives have prompted changes in regional energy policies (68). The disaster has resulted in enduring socio-economic decline and significant psychological consequences, such as increased stress and diminished quality of life for the impacted populations (72, 73).

The health consequences of CND are both immediate and long-term. Acute radiation syndrome resulted in the deaths of 28 emergency workers, with a total of 64 fatalities directly associated with the disaster (70, 74). Longitudinal studies indicate increased incidences of thyroid cancer, leukemia, and other malignancies, especially in children exposed to radiation (75). Mental health disorders such as anxiety, depression, and post-traumatic stress disorder are prevalent public health issues affecting survivors and workers (73). Documented secondary health effects include cardiovascular diseases, cataracts, and endocrine disorders among individuals exposed to lower radiation doses (75).

3.4.3 Long-term environmental and health surveillance

A fundamental insight from the CND is the necessity for ongoing, long-term monitoring of environmental and public health effects (61,

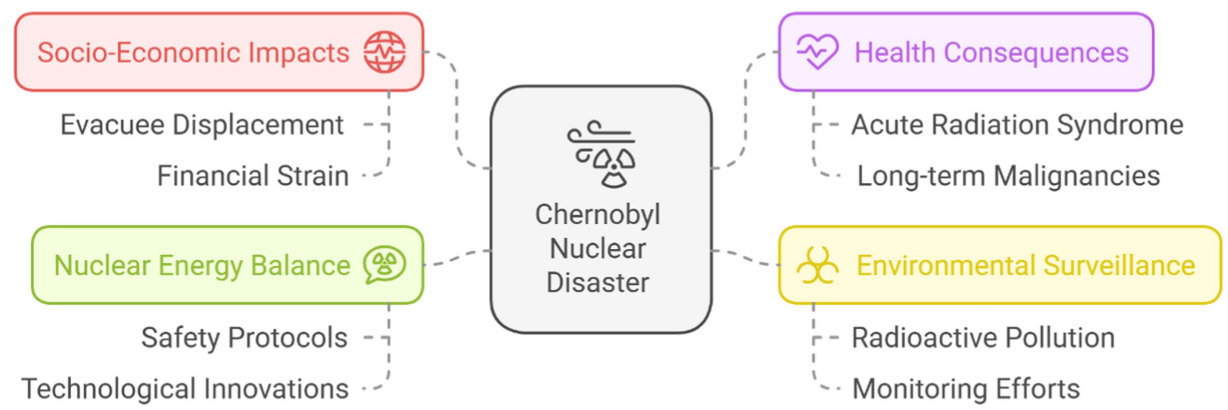

FIGURE 4
Overall prospective challenges and dilemmas from Chernobyl nuclear disaster based on the present literature review.

76). The enduring presence of radioactive pollution, attributed to isotopes with half-lives extending over decades, underscores the continuous risk to the area. This issue affects countries dealing with nuclear contamination, requiring significant investment in long-term monitoring and remediation strategies (23, 47). The high costs and complexities of such initiatives frequently strain resources, thereby complicating the prioritization of objectives. Monitoring radiation-induced health effects, including malignancies, necessitates ongoing investment in healthcare infrastructure and research, presenting considerable challenges for resource-limited countries (50, 62).

The environmental impact of CND was extensive and multifaceted. The release of radioactive materials contaminated land, water, and air throughout Europe, significantly impacting Belarus, Ukraine, and Russia (77, 78). The 30-kilometer exclusion zone surrounding the reactor is uninhabitable; however, it has unintentionally transformed into a wildlife sanctuary due to the lack of human presence, despite ongoing high radiation levels (70, 79). Although biodiversity experienced significant declines, certain species have adapted to the radioactive conditions, while others display genetic mutations (77). Additionally, radioactive isotopes have contaminated water systems, including significant rivers in Ukraine, presenting enduring risks to human and ecological health (80). The persistent environmental challenges highlight the need for continuous monitoring and global cooperation in tackling nuclear contamination.

3.4.4 International governance and accountability

The CND emphasized the importance of international cooperation in nuclear safety management and disaster response (47, 48). It is essential to develop robust global governance frameworks to prevent such tragedies. There are challenges regarding the assurance of equal accountability (15, 23). Certain nations have the scientific capacity to enhance nuclear safety, while others may lack the necessary resources or political will to achieve this (81, 82). Global governance processes must be inclusive, transparent, and effectively enforced. Accountability issues, particularly in relation to historical nuclear disasters, remain a significant obstacle to compensation and justice for affected communities (58, 64, 83–88).

The absence of a cohesive international framework for nuclear liability and disaster response hinders efforts to establish accountability and provide equitable support to affected nations (89–91). Disparities in financial responsibility, legal obligations, and enforcement mechanisms can impede collaborative progress and intensify tensions among nations with varying nuclear capabilities (48, 81). Establishing standardized protocols for nuclear disaster preparedness, compensation, and remediation is essential, supported by multilateral agreements and a strong enforcement mechanism. Enhancing the IAEA's role in compliance oversight and collaboration may address existing gaps and improve global nuclear safety (92–95).

3.4.5 Resilience against climate change

The ecological restoration in the Chernobyl Exclusion Zone offers important insights into resilience while also underscoring the difficulties of executing effective environmental protection strategies amid climate change (52, 96, 97). The rising incidence of natural disasters, industrial accidents, and ecosystem degradation associated with climate change necessitates that recovery efforts be sustainable and adaptable (47, 48, 98, 99). The main challenge is achieving a balance between human development and environmental conservation. Industrialized nations frequently emphasize energy and industrial development, whereas developing countries may be constrained by insufficient resources to support recovery efforts (57, 76). The disparity in resilience capacity poses substantial global challenges to climate change mitigation and disaster risk reduction, as indicated in the UNSDGs (56, 66).

The restoration efforts in Chernobyl underline the necessity for interdisciplinary approaches that combine ecological science, socio-economic policies, and technological innovation. Collaborative frameworks are crucial for tackling complex challenges, including radioactive contamination, biodiversity loss, and land-use planning in areas susceptible to disasters. Global partnerships and knowledge-sharing enable both industrialized and developing nations to improve their resilience strategies, aligning recovery efforts with climate adaptation goals and equitable resource distribution (48, 53). This approach supports long-term ecological sustainability and promotes a unified response to global climate-induced challenges.

3.4.6 Ethical quandaries in energy policy

Nuclear energy poses ethical challenges due to potential risks to human life and the environment (40, 53). Nuclear energy can meet the global demand for clean energy; however, the risk of catastrophic events, exemplified by Chernobyl, necessitates an assessment of whether the benefits outweigh the risks (59, 76). The management of nuclear waste, which poses risks for thousands of years, complicates energy policy decisions (18, 19). Policymakers face the ethical challenge of reconciling the immediate benefits of nuclear energy with its long-term environmental and health impacts, while also considering the responsibility of managing nuclear waste for future generations (22, 83, 100).

The CND serves as a critical case study for understanding the complex interplay among energy policy, environmental management, and public health (24, 45, 101). The global quest for sustainable solutions to climate change and energy requirements underscores the critical lessons from Chernobyl regarding the intrinsic risks and challenges linked to nuclear power (25, 62, 102). Balancing the demand for clean energy with safety, resilience, and ethical governance will continue to be a critical global challenge in the coming decades (24, 53).

4 Conclusion

The current assessment findings could provide crucial insights for advancing the UNSDGs, particularly in health, energy, climate action, and international collaboration. The global community must prioritize strong governance institutions, continuous environmental and health monitoring, and ethical energy policymaking. Achieving a balance between clean energy requirements and safety is critical, as is ensuring long-term ecosystem resilience and encouraging cross-border collaboration. The legacy of CND emphasizes the ongoing need for attention and innovation to prevent future nuclear tragedies while promoting sustainability. As a result, the CND has previously highlighted the link between human health, environmental sustainability, and institutional governance. This is required to reduce the long-term consequences of nuclear accidents. This may necessitate a comprehensive plan that includes environmental restoration, public health interventions, and a strong energy policy. The CND has sparked global discussion about the role of nuclear energy in sustainable development, imparting important lessons relevant to the UNSDGs. It is envisaged that incorporating the current findings into policy frameworks will result in a safer, more sustainable future while reducing the risks connected with nuclear technologies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

CY: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. KA-M: Funding acquisition, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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