

RESEARCH ARTICLE

Integrating Ibn Khaldun's ecological and economic insights into core themes of nuclear pollution research

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Nuclear contamination has become a global crisis that threatens ecological stability and socio-economic development. Existing research primarily evaluates nuclear pollution's impacts on ecosystems, public health, and economic stability, yet theoretical frameworks to address its broader socio-economic implications remain underexplored. This study examined the critical themes of nuclear pollution research through the lens of Ibn Khaldun's ecological and economic perspectives to highlight the interconnection of ecological balance, economic stability, and human civilization and emphasize how environmental and economic disruptions lead to societal decline. This study integrated Ibn Khaldun's theoretical framework with modern analysis to provide historical warnings about the long-term impacts of nuclear pollution, used bibliometric analysis to identify key themes in nuclear pollution research, and applied content analysis to interpret Ibn Khaldun's insights. The findings of this study underscored the potential threats of nuclear contamination and its implications for civilization's sustainability. As a retrospective study, this research distinguished itself from conventional approaches by drawing historical parallels to highlight the urgent need for sustainable policies and global cooperation to address nuclear pollution's ecological and economic risks.

Keywords: nuclear pollution; Ibn Khaldun; ecological; economic; civilization.

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Introduction

Environmental degradation, particularly nuclear contamination, has escalated into a pressing global crisis that threatens both ecological stability and socio-economic development [1-3]. The far-reaching consequences of nuclear contamination from ecosystem destruction to public health risks pose severe challenges to the global pursuit of sustainable development [2]. As global trade expands and the world economic system becomes increasingly interconnected, localized environmental events such as the

discharge of nuclear wastewater can trigger chain reactions that affect global economic stability [3]. For example, the release of radioactive waste into oceans not only endangers marine ecosystems but also impacts global food security, economic stability, and the reputation of affected regions [4-6]. Nuclear contamination affects various environmental components including water, air, and soil systems [7-11]. Nuclear effluents pose long-term threats to ecosystems and human health due to the persistence of radioactive isotopes such as tritium, which cannot be fully removed during

treatment processes [8, 9]. Water contamination can result in the bioaccumulation of harmful substances, impacting aquatic life and, subsequently, human health through the food chain [7, 10]. Airborne emissions of radioactive particles can deteriorate air quality, raising risks to human health and disrupting ecological balance [11-14]. Economically, nuclear contamination reduces consumer confidence in food safety, harming agricultural industries, and causing long-term economic instability [15, 16]. These issues highlight the urgency of addressing nuclear contamination's multidimensional impacts.

Ibn Khaldun, a prominent medieval scholar, offered a theoretical framework for understanding the interdependence among ecological balance, economic stability, and societal development [17-21]. His ecological insights emphasized the role of natural resources such as water and air quality in sustaining civilizations, while his economic theories highlighted the importance of sustainable resource management and the consequences of environmental neglect [18-20]. He argued that environmental degradation could accelerate economic decline and destabilize social structures, offering a historical perspective to analyze modern environmental crises [19, 20]. Despite extensive research on the environmental and economic impacts of nuclear contamination, theoretical frameworks to address its broader socio-economic implications remain underexplored. Most studies concentrate on immediate physical consequences instead of examining how ecological and economic disruptions affect societal stability and development. This study aimed to bridge this gap by integrating historical insights into contemporary scientific inquiry.

The purposes of this study were to analyze nuclear contamination's ecological and socio-economic impacts through a multidisciplinary approach, specifically, to examine the key environmental and economic consequences of nuclear contamination and explore how

historical insights, particularly Ibn Khaldun's theories, could inform modern sustainability practices. By synthesizing historical insights with modern analytical techniques, this research underscored the interconnection of environmental stability, economic resilience, and societal sustainability. As a retrospective study, the results of this study would highlight the long-term effects of nuclear contamination and emphasize the urgent need for sustainable policies and international collaboration to address the associated risks.

Materials and methods

Bibliometric analysis

This multidisciplinary study applied bibliometric and content analysis methods. Bibliometric analysis was primarily used to evaluate the fundamental topics in nuclear contamination research. During the data analysis, VOSviewer 1.6.18 (<https://www.vosviewer.com>) and Scimago Graphica (<https://graphica.app>) were employed as essential tools for uncovering the core themes within nuclear pollution research. The main aim of the content approach was to elaborate on Ibn Khaldun's ecological and economic perspectives, while examining the ecological and economic effects of nuclear contamination. The research data for this study were gathered from the Web of Science Core Collection database (<https://www.webofscience.com/wos/woscc/basic-search>). The criteria for selecting the research data included the topic (nuclear pollution), quick filters (open access), publication year (2019 - 2023), document type (article), Web of Science Index (Science Citation Index Expanded, Emerging Sources Citation Index, Arts & Humanities Citation Index, and Social Sciences Citation Index), and language (English). Based on these criteria, a total of 591 high-quality and relevant articles were selected for comprehensive visualization and analysis.

Data analysis

The data analysis began with data cleaning and standardization to ensure data consistency by

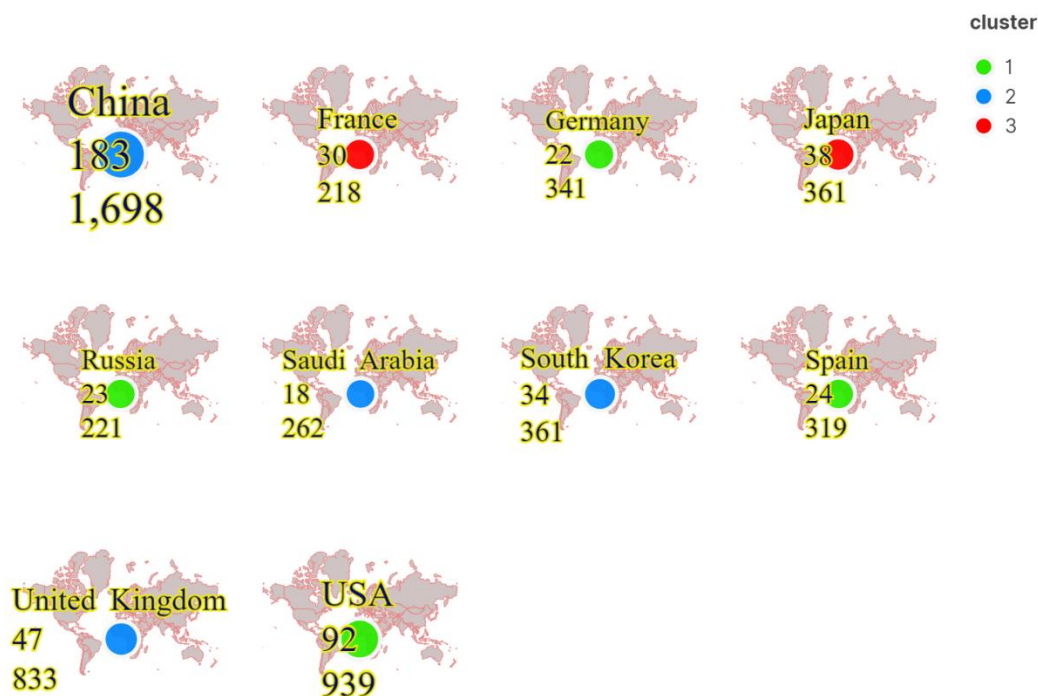


Figure 1. Top 10 countries with high publication volume and strong citation relationship.

removing duplicate records and merging synonyms. A minimum document count of 19 was established per country, while VOSviewer was utilized to create the initial map. The initial map was refined and visually enhanced using Scimago Graphica to create geographical visualization. Co-occurrence analysis was conducted with VOSviewer utilizing a threshold of minimum keyword occurrence as 15 times to identify thematic clusters. The keyword co-occurrence networks and overlay visualizations of temporal trends were then generated directly from VOSviewer.

Integration of Ibn Khaldun's ecological and economic insights

This study integrated Ibn Khaldun's ecological and economic insights using the content analysis method and applied his theoretical framework to interpret the findings of nuclear pollution. Ibn Khaldun's ecological perspective emphasized the intrinsic relationship between environmental stability and societal stability, arguing that environmental degradation accelerated societal decline. His economic perspective highlighted

the importance of sustainable resource management and warns of the severe consequences of environmental degradation.

Results and discussion

Top prominent countries documenting nuclear pollution

The rankings of the top ten nations based on their publication output and citation impact were depicted in Figure 1. The results showed that China's research efforts were highlighted by its impressive performance of 183 articles and an exceptional 1,698 citations, solidifying its leading position in the field. The United States of America closely followed and ranked the second with 92 publications and 939 citations. The United Kingdom ranked the third with 47 articles and 833 citations. In terms of international collaboration, these countries have formed highly interconnected citation networks, demonstrating a cooperative global research landscape, which is essential for addressing the complex issue of nuclear contamination as it

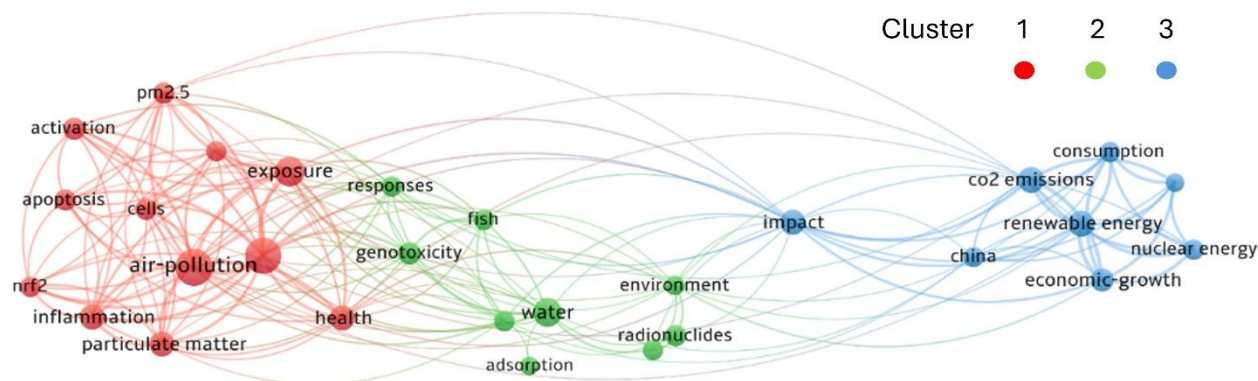


Figure 2. Keyword co-occurrence in the network of nuclear pollution studies.

required a multidisciplinary and multinational approach. Furthermore, three separate clusters that had highly interconnected citation links were identified with cluster 1 involved Germany, Russia, Spain, and the United States, cluster 2 comprised China, Saudi Arabia, the United Kingdom, and South Korea, and cluster 3 included France and Japan. The interconnection of these clusters illustrated the joint efforts of these countries in pursuing common research objectives, emphasizing the need for shared knowledge and strategies in tackling nuclear pollution.

Keyword co-occurrence of nuclear pollution studies

This research set the minimum co-occurrence of keywords at 15 and combined synonymous items, resulting in 29 relevant keywords. The co-occurrence network of keywords in nuclear pollution studies demonstrated three distinct clusters (Figure 2). Cluster 1 consisted of 12 nodes, focusing primarily on the impact of nuclear pollution on air resources. The most significant keyword in this cluster was air pollution with a total line strength of 165 and the occurrences of 74. Cluster 2 comprised 9 nodes, focusing on the impact of nuclear pollution on water resources. The most important keyword in this cluster was water with total line strength of 32 and the occurrences of 39. Cluster 3 included 8 nodes, emphasizing the impact of nuclear pollution on the development of renewable

energy and economic growth. The critical keyword in this cluster was renewable energy with a total line strength of 93 and the occurrences of 32. These clusters represented the core areas of concern in nuclear pollution studies with a focus on air and water contamination and their broader implications for renewable energy development and economic growth. The co-occurrence overlay network of nuclear pollution studies demonstrated that, by utilizing the overlay network, this study identified five recent prominent terms including nuclear energy with the occurrences of 18 and average publication year of 2,022.00, economic-growth with the occurrences of 25 and average publication year of 2,021.84, environmental Kuznets curve with the occurrences of 15 and average publication year of 2,021.80, CO₂ emission with the occurrences of 31 and average publication year of 2,021.71, and consumption with the occurrences of 17 and average publication year of 2,021.71 (Figure 3). The prominence of these keywords underscored the contemporary focus on the intersection between nuclear energy and environmental sustainability, emphasizing the increasing concern over carbon emissions and economic growth within the context of nuclear pollution.

Analysis of the ecological impacts of nuclear pollution through Ibn Khaldun's perspective

Although Ibn Khaldun's discussion of environmentally sustainable development was

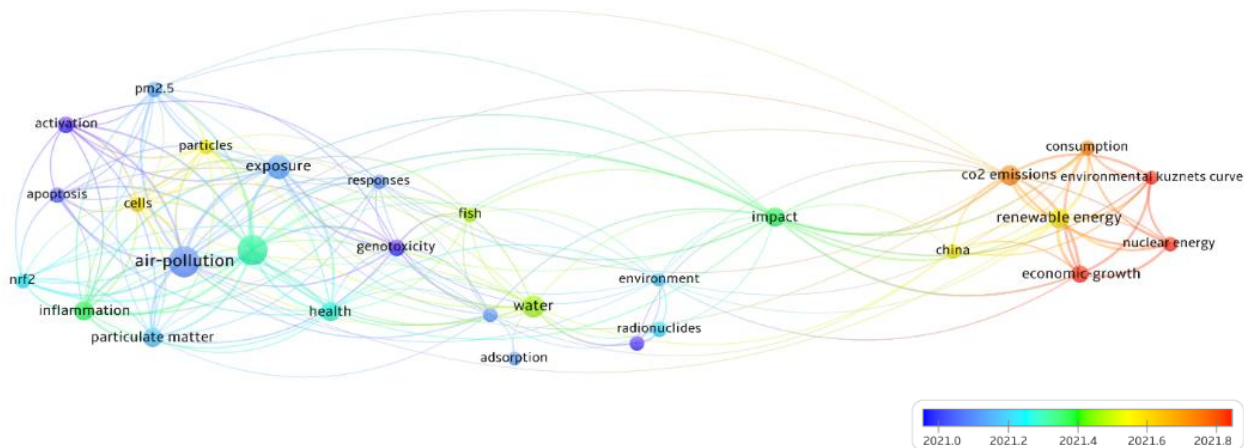


Figure 3. Keyword co-occurrence in the overlay network of nuclear pollution studies.

somewhat limited, he accurately acknowledged the natural environment's impact on humanity and human civilization. [22, 23]. Ibn Khaldun argued that the natural environment influenced individual qualities including physical appearance, mental well-being, personality, lifestyle, and general health. Furthermore, nature had significantly influenced the formation, advancement, and deterioration of human civilization [22]. From Ibn Khaldun's sociological framework, the relationship between humans and nature was integral to the sustainability of societies as ecological balance directly influenced social stability and progress [18]. In the context of nuclear pollution, Ibn Khaldun's understanding of environmental degradation could be extended to reflect how modern industrial pollutants like nuclear waste severely disrupted ecological systems, leading to significant harm to public health, societal well-being, and the sustainability of urban centers. Ibn Khaldun emphasized the importance of maintaining clean air and access to fresh water for sustaining healthy urban centers. He highlighted that polluted air and water contributed to the spread of diseases and the decline of urban populations [18-20]. Such observations underscored the broader implications of environmental degradation, which were equally relevant to the contemporary challenges posed by nuclear contamination. For instance, Akhtar *et al.* emphasized that

freshwater was essential for human survival and a critical driver of sustainable economic growth and civilizational progress [24]. Pollution of the vital natural resources that humans depend on will inevitably slow or even reverse the development of human society.

Analysis of the economic impacts of nuclear pollution through Ibn Khaldun's perspective

Agriculture is a fundamental and essential means of livelihood. Ibn Khaldun concluded that the quality of natural conditions and investments in land improvement, new crop cultivation, and advancements in agricultural technology directly impacted agricultural costs and, consequently, the prices of agricultural products. He reached this conclusion by comparing the agricultural practices of the Berbers who lived on fertile land to those of the Islamic followers who were expelled by Christians and settled on less fertile terrain [25-27]. In the context of nuclear pollution, contamination of agricultural land and water sources led to similar disruptions in agricultural production, negatively impacting food security, and contributing to price volatility in local and global markets [16]. The contamination diminished agricultural output, driving up production costs, and harming both local economies and international trade flows [15, 16]. Labor value is integrated into the value of commodities and enters the market, transforming into profits that circulate to the

workers through transactions. Hence, the accumulation of societal prosperity and the attainment of well-being for people are accomplished through the value generated by labor [26, 27]. To facilitate the flow of goods in the market, it is necessary to ensure that the products retain utility according to consumers' purchasing preferences, hence enabling the conversion of labor value into profit. When customers exhibit a negative inclination to make purchases, it hinders the movement of commodities and results in a decline in the demand for goods. At this juncture, the production yield of the commodity, the labor demand required for its production, and the commodity's price will all decrease. In the case of nuclear contamination, consumer distrust in food safety further reduced demand for agricultural products from affected regions, leading to broader economic disruptions including a decline in labor demand and production activity [5, 15, 16]. Given the interconnection of the economic market, fluctuations in the price of one item typically have an impact on the cost of another, eventually influencing the trajectory of the economy and the advancement of urban civilization. Ibn Khaldun's economic theory is deeply linked to society's advancement, political systems' stability, and the trajectory of human civilization [28, 29]. He highlighted the government's regulatory function in economic activities and the substantial influence of policies on the market [26-29]. In Ibn Khaldun's view, effective governance ensured a balance between justice, economic development, and social cohesion. Essentially, he created a circular structure that encouraged the ongoing progress of civilization, and it was crucial to guarantee that every element inside it was positive [30]. While academics had examined the elements in this cycle to different extents, they generally concurred that the primary factors consisted of the regime, economy, social cohesion, development, and justice. Justice and development are the fundamental components of the entire cycle system with people's solidarity as the motivating factor supporting positive

growth [30, 31]. Ibn Khaldun discussed the significance of social cohesiveness in economic development and civilizational advancement although he did not explicitly refer to an extensive range of people when discussing solidarity. To maintain a sustained level of social cohesiveness, it is crucial to have strong leadership, adherence to ethical standards, fair tax policies, dedication to the well-being of people in general, and responsiveness to public feelings [32]. In the case of nuclear pollution, the erosion of public trust in authorities that failed to regulate environmental risks undermined social cohesiveness, disrupting the economic and political stability necessary for the continued advancement of civilization [3]. Moreover, economic policies that imposed excessive burdens on workers diminished their work motivation and impeded industrial activity, ultimately resulting in an economic downturn and a decline in national tax revenues [33]. Decreased tax revenues could subsequently affect national defensive expenditures, threatening national security, and ultimately leading to the downfall of the state and the collapse of civilization [26, 33]. Similarly, the negative economic impacts of nuclear contamination such as damage to public health and diminished consumer demand could reduce tax revenues, undermining a country's capacity to fund essential services and ensure national security [3, 34]. Hence, the presence of nuclear pollution will eventually jeopardize the survival of nations and lead to the downfall of civilizations.

Conclusions

The release of radioactive pollutants poses a serious threat to both the environment and the global economy. Recent research has focused on nuclear pollution's ecological and economic consequences, particularly its impact on public health, agriculture, and urban development. By applying Ibn Khaldun's ecological and economic theories, this study highlighted how environmental degradation including nuclear

contamination disrupted societal stability and economic growth. Ibn Khaldun's emphasis on natural resources such as water and air were highly relevant to understanding the modern challenges posed by nuclear pollution. His economic insights into labor value and justice further highlighted the necessity for robust regulatory policies to address environmental crises. Although Ibn Khaldun's ideas originated in a different era, their significance in relation to contemporary issues like nuclear pollution demonstrated the enduring importance of sustainability governance. The findings of this study suggested that nuclear pollution like other environmental issues demanded coordinated global action and stringent regulations to protect ecological and economic sustainability. This study advocated for stronger international cooperation and long-term strategies to safeguard human welfare and ensure the sustainable development of civilization.

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