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COMPETENCY-BASED HUMAN RELIABILITY: FEMALE PARTICIPATION AS A DRIVER OF WORKFORCE SUSTAINABILITY IN THE NUCLEAR SECTOR

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1. Introduction

Climate change, growing energy demand, and the need to reduce greenhouse gas emissions have repositioned nuclear energy as a strategic component of the global energy transition [1]. In Brazil, initiatives such as the completion of Angra 3 Nuclear Power Plant and the development of the Brazilian Multipurpose Reactor (RMB) reinforce the need to expand the availability of highly qualified professionals capable of supporting the safe and sustainable growth of nuclear activities [2]. Consequently, nuclear safety increasingly depends not only on the integrity of technological systems but also on organizations' ability to develop, preserve, and mobilize critical organizational competencies and knowledge over time [1,2]. Workforce sustainability has therefore become a strategic challenge for the nuclear sector. Workforce ageing, the retirement of experienced specialists, increasing competition for qualified professionals, and the potential loss of organizational knowledge threaten the long-term continuity of nuclear programmes [2–4]. International organizations recognize that attracting, developing, retaining, and transferring qualified professionals while preserving critical organizational competencies and knowledge is fundamental to ensuring operational continuity and sustaining nuclear safety [2–4]. The concept of human reliability has also evolved beyond traditional approaches focused primarily on individual error prevention. Contemporary studies emphasize that reliable organizational performance depends on competency management, knowledge management, continuous learning, and organizational adaptability within complex operational environments [1,6,8,9,16]. Accordingly, human reliability should be understood as an organizational capability to preserve, mobilize, and continuously renew the competencies and knowledge required to sustain high levels of safety and operational performance. Within this context, female participation should be regarded not only as an issue of diversity and equity but also as a strategic opportunity to strengthen workforce sustainability. Reports published by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA) indicate that women remain underrepresented in technical and leadership positions throughout the nuclear sector [3,4]. Expanding female participation broadens and diversifies the available talent pool, supporting the attraction, development, and retention of qualified professionals while contributing to the preservation of critical organizational competencies and knowledge. Previous studies further suggest that diverse teams may enhance innovation, organizational learning, and leadership development when supported by inclusive organizational environments and effective institutional policies [3,4,10–12]. Although competency management, workforce sustainability, female participation, and human reliability have each received considerable attention, these topics have generally been investigated independently. Studies integrating these concepts within a single theoretical perspective remain limited. To address this gap, this study proposes a Conceptual Framework that explains how competency management and female participation contribute to preserving critical organizational competencies and knowledge, thereby strengthening workforce sustainability and competency-based human reliability in nuclear organizations. The proposed framework provides a theoretical basis for future empirical research and for the development of organizational strategies aimed at strengthening nuclear safety.

2. Methodology

This study was conducted as a structured narrative literature review adopting a qualitative approach supported by the analysis of technical publications issued by the International Atomic Energy Agency

(IAEA), the OECD Nuclear Energy Agency (OECD/NEA), seminal books, and peer-reviewed literature addressing competency management, knowledge management, workforce sustainability, female participation, human reliability, and High Reliability Organizations (HROs). The reviewed publications were selected according to their relevance to the research question, while studies focused exclusively on technological aspects without addressing human or organizational dimensions were excluded. The literature was examined through a thematic integration of evidence, identifying the principal concepts, their theoretical relationships, and complementary perspectives across the reviewed studies. The integrated evidence supported the development of the Conceptual Framework proposed in this study, which synthesizes the relationships among competency management, preservation of critical organizational competencies and knowledge, female participation, workforce sustainability, and competency-based human reliability within nuclear organizations. The findings presented in the Results and Discussion section correspond to the synthesis of the reviewed literature, whereas the proposed Conceptual Framework represents the authors' theoretical interpretation of the integrated evidence. Therefore, the framework does not establish causal relationships or constitute empirical validation, but rather provides a theoretical basis for future empirical research.

3. Results and Discussion

The reviewed literature demonstrates that human reliability has progressively evolved beyond traditional approaches centered on individual error prevention. Within nuclear organizations, reliable performance is increasingly understood as the outcome of interactions among individual competencies, organizational processes, knowledge management, continuous professional development, and institutional capabilities operating in complex environments [1,6,9,16]. Consequently, competency management should be regarded not only as a human resource development practice but also as a strategic organizational mechanism for ensuring the safe continuity of nuclear operations. In this study, critical organizational competencies and knowledge are understood as the integrated set of explicit and tacit knowledge, technical and behavioral competencies, accumulated operational experience, and organizational capabilities required to ensure safe and reliable nuclear operations. Their preservation depends on organizations' ability to identify, develop, retain, transfer, and continuously renew these strategic assets throughout the workforce lifecycle, thereby mitigating the risks associated with workforce ageing, retirement, and employee turnover [2,5,8]. Accordingly, competency management integrates professional development, knowledge management, and knowledge transfer processes to preserve these strategic assets, providing the organizational basis for competency-based human reliability. The literature further identifies workforce sustainability as one of the major strategic challenges facing the long-term continuity of nuclear programmes [2–4]. This challenge extends beyond the availability of qualified professionals and is fundamentally associated with the organizational capability to preserve critical organizational competencies and knowledge over time. Knowledge management, succession planning, talent retention, and continuous professional development collectively support the continuity of these capabilities, enabling organizations to attract, develop, retain, renew, and transfer competencies across successive generations while reducing the risk of intellectual capital loss [2,8]. Within this context, female participation emerges as a strategic organizational resource rather than solely as an issue of diversity and equity. Reports published by the IAEA and the OECD Nuclear Energy Agency (OECD/NEA), together with Brazilian studies, indicate that women remain underrepresented in technical and leadership positions throughout the nuclear sector [3,4,13–15]. Expanding female participation broadens and diversifies the available talent pool, supporting the attraction, development, and retention of qualified professionals while contributing to the preservation of critical organizational competencies and knowledge. The literature also suggests that diverse teams may promote innovation, organizational learning, communication, and leadership development when supported by inclusive organizational environments and institutional policies [3,4,10–12]. Therefore, the potential benefits associated with diversity should be understood as organizational outcomes resulting from effective management practices rather than from gender diversity alone. The thematic integration of the reviewed evidence supported the development of the Conceptual Framework presented in Figure 1.

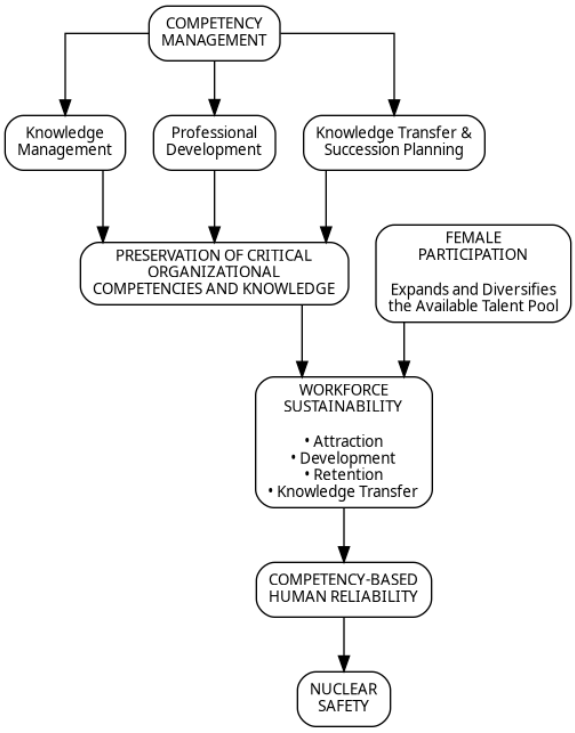


Figure 1. Conceptual framework illustrating the theoretical relationships among competency management, preservation of critical organizational competencies and knowledge, workforce sustainability, female participation, competency-based human reliability, and nuclear safety. The framework represents a theoretical synthesis derived from the reviewed literature and does not imply empirically validated causal relationships. Source: Prepared by the authors.

The framework proposes that competency management constitutes the central organizational mechanism through which critical organizational competencies and knowledge are identified, developed, retained, transferred, and continuously renewed. Their preservation strengthens workforce sustainability by ensuring the continuity of a qualified workforce, while female participation contributes by expanding and diversifying the available talent pool. Collectively, these organizational mechanisms support competency-based human reliability, ultimately contributing to nuclear safety. As a theoretical proposition derived from the reviewed literature, the framework neither establishes causal relationships nor provides empirical validation; rather, it offers a conceptual basis for future empirical research and organizational strategies aimed at strengthening workforce sustainability and human reliability within nuclear organizations.

4. Conclusions

The literature on competency management, knowledge management, workforce sustainability, female participation, and human reliability has largely evolved through independent research streams, limiting an integrated understanding of how these concepts interact within nuclear organizations. This structured narrative literature review addressed this gap by proposing a Conceptual Framework that synthesizes the theoretical relationships among these elements and explains how they collectively support competency-based human reliability. The reviewed evidence suggests that competency management constitutes a central organizational mechanism for preserving critical organizational competencies and knowledge, thereby supporting workforce sustainability and strengthening human reliability. Within this framework, female participation contributes by expanding and diversifying the available talent pool, supporting the attraction, development, and retention of qualified professionals. As a conceptual study, this research does not provide empirical validation of the proposed relationships. Instead, the framework should be interpreted as a

theoretical model intended to guide future empirical investigations and support organizational strategies aimed at strengthening workforce sustainability, competency based human reliability, and nuclear safety.

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