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Exploring Engineers' Experiences with Human-Robot Interaction in Smart Factories: A Phenomenological Approach

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ABSTRACT

The integration of robotics and artificial intelligence (AI) in smart factories is reshaping traditional manufacturing processes, requiring significant adaptation from engineers and operators. While much research has focused on the technical aspects of automation, less attention has been given to the psychosocial dimensions of workers' adaptation to robotic systems. Existing studies largely ignore how psychological and emotional responses impact the adaptation process, raising the question: How do engineers and operators experience and interpret their changing roles in automated environments?
A phenomenological approach is well-suited to answer this question, providing deep insights into the lived experiences of workers navigating the transition to robotic systems in smart factories. Using hermeneutic phenomenology, in-depth interviews were conducted with 15 engineers and operators, allowing exploration of cognitive and emotional challenges encountered during adaptation.
The findings reveal that workers undergo significant role transformations, grappling with emotional resistance and trust-building with robots, alongside developing new responsibilities in system optimization. These psychosocial shifts were key to understanding how workers adjust to automation beyond technical tasks, offering a richer perspective on their adaptation journey.
The study enhances our understanding of human-robot interaction by shedding light on the psychological factors influencing adaptation, with implications for improving workplace strategies and training programs to better support employees in automated environments.

INTRODUCTION

The integration of robotic automation and artificial intelligence (AI) in industrial manufacturing has significantly transformed traditional work environments, introducing new challenges and opportunities for human workers. As industries embrace smart factory systems, engineers and operators are increasingly required to interact with robotic systems that function autonomously, making real-time decisions and optimizing production processes. This shift marks a departure from conventional manual operations, placing human workers in supervisory roles that demand new cognitive, technical, and adaptive capabilities (Carmichael dkk., 2023).

While the adoption of robotics has been widely studied in terms of technological efficiency, productivity gains, and system optimization, less attention has been given to the human experience of engineers and operators who navigate these changes. The integration of Cyber-Physical Systems (CPS) and AI-driven automation not only alters workflows but also redefines professional identities, challenges existing skill sets, and reshapes human-robot interaction in industrial settings (Khumalo dkk., 2024). These changes are not purely operational; they involve psychosocial dimensions, including emotional responses, trust-building with machines, and cognitive shifts in decision-making. The adaptation process requires engineers to reconfigure their roles, develop new competencies, and establish effective communication with robotic systems—often under conditions of high uncertainty and organizational pressure (Assefa Tofu & Wolka, 2023).

Given these profound transformations, there is a growing need to explore how engineers and operators subjectively experience and interpret their interactions with robotic systems. This study aims to address the gap in understanding how engineers and operators adapt psychologically, cognitively, and emotionally to the integration of robotic systems in smart factories. A phenomenological approach allows for a deeper investigation into the lived experiences of individuals adapting to automation, uncovering their perceptions, challenges, and evolving professional roles. Unlike traditional quantitative assessments that measure task performance and efficiency, phenomenology provides rich qualitative insights into the meaning and significance of human adaptation within these evolving industrial ecosystems. Understanding these experiences is crucial for developing workplace strategies, training programs, and organizational policies that support seamless human-robot collaboration while addressing psychological and cognitive barriers.

Thus, this study seeks to bridge the gap between technological advancements and human adaptation by exploring the subjective realities of engineers and operators. Through a phenomenological lens, this research aims to capture the essence of their experiences, the cognitive and emotional dimensions of their adaptation, and the evolving interplay between human expertise and machine intelligence in smart factory environments.

Research on human experiences in technological transformation has gained increasing attention, particularly in the context of automation and artificial intelligence (AI) integration in industrial environments. As manufacturing shifts toward Industry 4.0, the role of engineers and operators is evolving from direct mechanical control to supervisory and decision-making functions, requiring them to engage with robotic systems in new and complex ways (Gosnell dkk., 2019). While previous studies have extensively examined the technical aspects of robotics implementation, there remains a significant gap in understanding how human workers adapt to these changes on a psychological, cognitive, and emotional level (Heider dkk., 2023). This transformation is not merely about skill acquisition but also involves identity reconstruction, trust-building with automated systems, and shifts in professional autonomy.

Despite the increasing relevance of human-robot interaction (HRI) in smart manufacturing, much of the existing research relies on quantitative performance metrics, operational efficiency assessments, and system optimization models (How dkk., 2020). While these approaches provide valuable insights into the functionality of robotic systems, they often fail to capture the subjective dimensions of human adaptation, such as the sense of agency, professional fulfillment, and the cognitive challenges involved in working alongside machines. Traditional methodologies in industrial research tend to focus on task execution and workflow efficiency, overlooking the personal experiences, concerns, and meaning-making processes of engineers and operators.

Addressing this methodological limitation, phenomenological inquiry offers a robust framework for exploring lived experiences, enabling researchers to uncover the deeper meanings behind human adaptation to automation. Unlike structured surveys or observational studies that quantify interaction patterns, phenomenology allows for a rich, descriptive account of how individuals navigate and interpret technological transitions. This approach is particularly suited for examining how engineers and operators perceive their changing roles, the psychological impact of automation, and the interplay between human cognition and machine intelligence (Ofuoku & Ekorhi-Robinson, 2020).

Given these complexities, a phenomenological approach is essential for capturing the nuanced realities of human engagement with robotic systems in smart factories. By delving into the personal accounts of engineers and operators, this study seeks to fill the gap left by predominantly quantitative research, offering a deeper, experience-based understanding of how automation shapes human work and identity.

While existing research on robotic automation and human-robot interaction in manufacturing has provided valuable insights into technological performance and efficiency, it largely overlooks the

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subjective experiences of engineers and operators. Much of the focus has been on quantitative analyses of productivity and system optimization, often using practical, metrics-driven approaches (Hien & Bao, 2024). These methods, while effective in measuring outcomes such as error rates, system uptime, and task efficiency, fail to capture the deep, lived experiences of individuals interacting with robotic systems. As a result, the emotional, cognitive, and psychological dimensions of human adaptation to automation remain underexplored. This oversight limits our understanding of the full scope of human-robot collaboration, particularly in terms of how workers emotionally and cognitively adapt to new roles and responsibilities within a technologically advanced workspace (Alotaibi dkk., 2021).

Existing methodologies also fail to address the complexity of personal identity transformation that occurs as engineers and operators transition from traditional roles to those involving robot oversight. These experiences involve changes in self-perception, professional fulfillment, and trust in technology, dimensions that are difficult to capture through conventional performance metrics. The practical, outcome-focused approaches commonly used in industrial studies cannot fully explore the psychosocial factors that influence human behavior, meaning-making, and adaptation in such environments.

A more comprehensive approach is needed to explore the subjective meanings and lived experiences of those working with robotic systems. Phenomenology, with its focus on capturing the essence of human experiences, offers a promising solution. By using in-depth, qualitative methods to delve into the psychological and emotional aspects of human-robot interaction, this approach can uncover the underlying meanings behind workers' responses to automation and provide a more holistic understanding of their adaptation processes. This study seeks to fill the gap left by previous research, offering a richer, more nuanced exploration of how engineers and operators perceive, interpret, and respond to the introduction of robotic systems in manufacturing.

Recent studies have explored various facets of human-robot interaction (HRI) and its impact on workers in automated environments, particularly within smart factories. Literature has focused on cognitive load and the emotional impact of robotics, noting that engineers and operators often experience a shift in their professional identity and roles (Prazeres dkk., 2023). Theories such as technology acceptance models and socio-technical systems theory provide frameworks for understanding how individuals adapt to technological change. However, these studies tend to concentrate more on quantitative metrics and overlook the personal and subjective experiences of workers in the face of automation (Taranov & Kawabata, 2024). This gap underscores the need for a deeper exploration of the psychosocial dimensions of adaptation in the context of robotic integration.

The approach adopted in this study is phenomenological, specifically using the hermeneutic phenomenological method. This methodology is selected because it allows for an in-depth exploration of the meaning-making processes of engineers and operators who interact with robotic systems in manufacturing settings. Unlike traditional quantitative methods, phenomenology emphasizes lived experiences and seeks to uncover the essence of how individuals perceive and adapt to new technologies. By applying this approach, this research aims to address the gap identified in the Knowledge Gap section, providing insights into the cognitive, emotional, and social adaptation that engineers undergo when integrating automation into their daily workflows.

This article is structured as follows: an Introduction, which includes a background of the phenomenon and the research questions; a Methodology section, outlining the phenomenological approach used to collect and analyze data; followed by the Results, which present the key themes identified from the data. The article will then discuss the findings in relation to existing literature, before concluding with a summary of insights, their implications for practice, and recommendations for future research. The focus throughout is on capturing the lived experiences of engineers and operators, offering a comprehensive understanding of how these individuals navigate their roles in smart factories.

RESEARCH METHODS

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Study Design

This study employed a hermeneutic phenomenological approach, which focuses on exploring and interpreting the lived experiences of engineers and operators adapting to human-robot interaction in smart factories. Phenomenology was chosen as the research design due to its capability to capture the depth of subjective experiences, providing insights into how individuals construct meaning around technological changes in industrial settings (Jezeer dkk., 2019). By emphasizing the engineers' perceptions, challenges, and cognitive responses, this approach ensures a holistic understanding of the psychological and professional adaptations required in a robotics-driven environment.

Hermeneutic phenomenology, as conceptualized by Heidegger, was applied to investigate the deeper meanings embedded in participants' experiences rather than merely describing them. This approach facilitated an interpretative analysis of how individuals make sense of their interactions with robotic systems, moving beyond surface-level narratives to uncover the underlying cognitive and emotional adjustments involved in the adaptation process.

Participants

The study involved engineers and operators working in smart factory environments where robotic automation had been implemented. Participants were selected using purposive sampling, ensuring that they had substantial exposure to human-robot interaction in manufacturing settings. Inclusion criteria required participants to have at least three years of experience in smart factories, direct involvement in managing robotic systems, and willingness to provide in-depth reflections on their adaptation processes. Those with limited exposure to robotics in industrial settings or who were in non-technical managerial roles were excluded to maintain data relevance.

A total of 15 participants were included in the study, consisting of 10 engineers and 5 operators, with an age range of 28 to 52 years. The sample size of 15 participants was determined based on the principle that phenomenological research aims to achieve depth rather than breadth, and that saturation—where no new themes emerge from further data collection—can often be reached with a relatively small sample size. This approach is in line with the guidance provided by phenomenological research methodologies, where rich, detailed accounts of experiences are more critical than large numbers. The participants' backgrounds varied in terms of expertise in automation, robotics, and industrial systems (Miyake dkk., 2022). To ensure diversity, individuals from different factory environments and organizational structures were included, allowing for a comprehensive exploration of experiences related to robotic integration.

Data Collection

Data were collected through in-depth semi-structured interviews, allowing participants to describe their experiences freely while ensuring the discussion remained focused on key aspects of human-robot interaction. Interviews were conducted face-to-face in private settings within the participants' workplaces to provide a familiar and comfortable environment. Each session lasted between 45 and 90 minutes, depending on the depth of responses.

A set of open-ended guiding questions was used to encourage detailed reflections, covering themes such as the initial adaptation process, cognitive and emotional challenges, changes in job roles, and perceptions of robotic reliability. To enhance data richness, follow-up questions were used when necessary to probe deeper into specific experiences. All interviews were audio-recorded with participants' consent and later transcribed verbatim for analysis. Field notes were also maintained to capture non-verbal cues and contextual observations that could aid in interpreting the findings.

Data Analysis

The data were analyzed using Interpretative Phenomenological Analysis (IPA), following a systematic approach to identifying themes that encapsulate participants' lived experiences. Transcribed interviews were imported into NVivo software to facilitate organization and coding of emerging themes.

The analysis followed these structured steps:

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1. Initial Reading & Familiarization: Transcripts were read multiple times to gain an overall understanding of participants' narratives.
2. Identification of Meaning Units: Key phrases and statements reflecting experiences of human-robot adaptation were highlighted and coded.
3. Theme Extraction: Codes were categorized into higher-order themes, such as cognitive adaptation, trust-building, and resistance to automation.
4. Interpretative Analysis: The themes were further examined to uncover underlying meanings, linking individual experiences to broader patterns.
5. Validation & Refinement: Themes were cross-checked against field notes and reviewed iteratively to ensure credibility.

To maintain analytical rigor, triangulation was conducted by comparing findings across multiple participants and incorporating feedback from industry professionals who reviewed preliminary interpretations. This ensured that the identified themes accurately represented the lived experiences of engineers and operators.

Ethical Considerations

Ethical approval for this study was obtained from the relevant institutional ethics review board, ensuring compliance with research guidelines on human subjects. All participants were provided with detailed information about the study's objectives, their rights, and the confidentiality of their data. Informed consent was obtained in written form before conducting interviews, and participants were assured of their right to withdraw from the study at any stage without consequences.

To maintain confidentiality, participant identities were anonymized using pseudonyms, and any identifiable workplace details were omitted from the transcripts. Data security protocols were followed, with all recordings and transcripts stored on encrypted servers accessible only to authorized researchers. This study adhered to ethical standards outlined by the Declaration of Helsinki and relevant industrial research ethics guidelines.

RESULTS

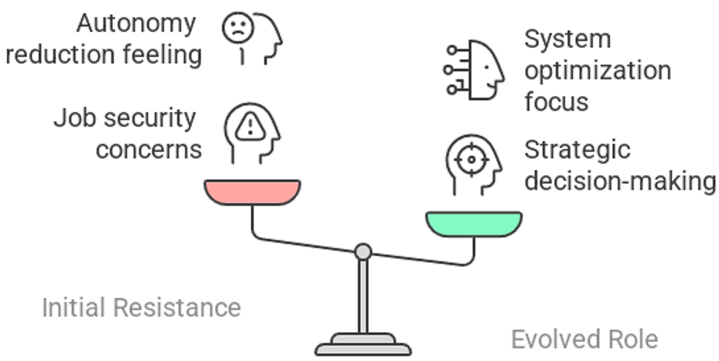
Engineers' Adaptation to the Presence of Robots in Smart Factories

One of the most salient themes emerging from the data is the engineers' adaptation process when integrating robots into smart factory environments. The participants consistently described a transformative shift in their professional roles, transitioning from direct mechanical intervention to supervisory and optimization tasks. Several engineers expressed an initial resistance to the presence of robotic systems, stemming from concerns about job security and the perceived reduction in their autonomy over machine processes.

"At first, I felt like my expertise was being undermined. I had spent years mastering manual interventions in the production line, but suddenly, the system required me to rely on algorithms and robotic adjustments instead of my own judgment." (Participant 4)However, over time, many engineers developed a new perspective, acknowledging that their expertise was still crucial—albeit in different ways. Rather than directly controlling machinery, they shifted towards ensuring seamless human-robot collaboration, troubleshooting advanced automation systems, and making strategic decisions based on data-driven insights.

"Eventually, I realized that my role was not diminished but rather evolved. Now, I focus on system optimization and analyzing robot efficiency instead of manually fixing errors." (Participant 7)

Engineers' Transition from Resistance to Adaptation



Psychological and Cognitive Load in Human-Robot Interaction

The second major theme highlights the cognitive and psychological load experienced by engineers and operators as they adapt to human-robot interaction in smart factories. Many participants reported experiencing mental fatigue due to the need to understand complex algorithmic decision-making and troubleshoot robotic malfunctions beyond traditional mechanical failures.

"I used to be confident in troubleshooting mechanical problems, but with robots, the errors are not always physical. Sometimes it's a software issue, sometimes a sensor misalignment. This creates an added layer of stress because we have to diagnose beyond what we are traditionally trained for." (Participant 2)

Engineers also described an increased reliance on continuous learning and upskilling, which was both a necessity and a source of cognitive strain. The expectation to stay updated with AI-driven automation and predictive maintenance systems led some to feel overwhelmed, particularly those who had spent years working in conventional industrial settings.

"We have to constantly train ourselves to keep up with new AI updates. Unlike mechanical systems, these robots are continuously evolving, so learning never stops." (Participant 6)

Resistance and Trust Issues in Robot Integration

Another recurring concern in the data revolves around the engineers' initial resistance and subsequent trust-building process with robotic systems. The skepticism toward automated systems primarily stemmed from concerns over unpredictable robot errors and a lack of transparency in AI-driven decision-making. Some engineers feared that over-reliance on robots could compromise safety and reduce the workforce's control over production processes.

"Robots are precise, but they are not flawless. There are times when the system fails to detect anomalies, and that's when things get complicated. We still need human intervention." (Participant 8)

Trust issues were gradually mitigated as engineers gained familiarity with robotic systems through iterative interaction. Many reported that hands-on experience and deeper engagement with the system improved their confidence in automation. Nonetheless, concerns remained regarding ethical considerations, such as the accountability of decision-making in case of system failures.

"With time, I learned to trust the system more, but we still need clear guidelines on who is accountable when an AI-driven machine makes a wrong decision." (Participant 5)

The Changing Role of Engineers in Smart Factories

The introduction of robotics in manufacturing is redefining the traditional roles of engineers. The findings indicate that rather than eliminating the need for human expertise, smart factories are reshaping engineering responsibilities. Engineers are increasingly tasked with overseeing real-time analytics, managing robotic troubleshooting, and optimizing predictive maintenance algorithms.

"I don't spend my time manually adjusting machines anymore. Instead, I oversee a network of robotic systems and ensure they operate as efficiently as possible." (Participant 3)

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Additionally, the engineers acknowledged the need for interdisciplinary collaboration, particularly with data scientists and AI specialists, to fully leverage automation potential.

"It's no longer just about mechanical engineering. We work closely with AI developers now, combining our domain expertise with their knowledge in algorithms to refine robotic processes." (Participant 1)

The overall findings illustrate that while engineers face initial psychological and cognitive challenges when adapting to human-robot interaction in smart factories, their roles are evolving rather than becoming obsolete. The study highlights the dual nature of automation: it introduces complexity and stress but simultaneously expands professional opportunities through advanced system optimization. Engineers are not merely passive adopters of robotic technologies; they actively shape the integration process, ensuring that automation enhances rather than disrupts industrial workflows.

Despite technological advancements, trust in automation remains a significant factor in successful implementation. While engineers gradually develop confidence in robotic systems, concerns regarding accountability and safety persist. These findings suggest that successful adaptation to smart factories requires not only technical training but also a focus on human factors, psychological resilience, and collaborative interdisciplinary work.

DISCUSSION

Summary of Key Findings

The study reveals that the integration of robotic systems in smart factories has a profound impact on engineers' and operators' roles, reshaping their professional identities and cognitive processes. The adaptation to automation involves both emotional and cognitive challenges, including initial resistance, the building of trust in robotic systems, and the transformation of job functions into supervisory and analytical roles. These findings address the central question of how engineers and operators experience and adapt to robotic systems in industrial settings, highlighting the psychosocial dimensions that remain underexplored in previous research.

Contribution to Research Questions

This research significantly contributes to our understanding of how engineers and operators experience the integration of robots into smart factories. The study highlights that adaptation is not simply a technical adjustment but involves a complex psychological and cognitive process, in which workers must navigate changes in their roles, trust in automation, and identity. The findings provide insight into the cognitive dissonance engineers face when confronted with the loss of direct control over the machines they once managed. Moreover, the research underscores that while technological adaptation is crucial, it is equally important to address the psychosocial factors that affect workers' acceptance and confidence in robotic systems. To ensure effective adaptation, it is recommended that organizations incorporate both technical training and psychosocial support, such as mentorship programs and stress management workshops, to help workers adjust to new roles and foster trust in automation. This exploration offers a holistic perspective on the human side of industrial automation, which has been largely neglected in traditional studies focused on efficiency and technical optimization.

Relation to Previous Literature and Theoretical Framework

The findings align with and extend the existing literature on human-robot interaction (HRI) and cognitive load in the context of automation. Previous studies have primarily emphasized the technical aspects of robotic integration, such as performance improvements and system efficiency, often overlooking the psychological adaptation of workers (Singh dkk., 2022). This study complements these findings by providing a deeper insight into the emotional and cognitive responses that accompany technological change, specifically in terms of how workers renegotiate their professional identities.

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Furthermore, the findings resonate with socio-technical systems theory, which posits that the success of technological systems depends not only on their technical performance but also on the social system within which they operate (Zwane, 2019). The experiences of engineers and operators in this study emphasize the critical need for a balanced integration of both technical and human factors, reaffirming the importance of addressing psychosocial dimensions in the design and implementation of automated systems. This theoretical lens enriches our understanding of the interdependence between human and machine in the workplace, offering valuable insights for future research and practice in industrial automation.

Explanation of the Implications of the Findings

The findings from this study have both scientific and practical implications for the integration of robotic systems in industrial settings. From a scientific perspective, the results underscore the importance of examining psychosocial factors in the workplace, particularly in relation to the adaptation of workers to automation. The emotional and cognitive experiences of engineers and operators, as revealed through their narratives, provide valuable insights into the human side of technological change, which is often neglected in technical studies. This highlights the need for a multidisciplinary approach that includes both technical and psychological perspectives when designing and implementing smart factory systems.

From a practical standpoint, the findings suggest that companies and organizations should not only focus on training workers to operate robotic systems but also on supporting their emotional and cognitive adaptation. Creating environments that foster trust in automation and provide adequate resources for role transition can significantly enhance the effectiveness of smart factories. For instance, ensuring that workers feel empowered in their new roles, such as system optimization or troubleshooting, can help mitigate feelings of job insecurity and resistance to change. This approach is particularly relevant in the context of the current global shift toward automation, as it emphasizes the need for a holistic view of human-robot collaboration that acknowledges both the technical and human dimensions.

Limitations of the Study

While this study provides valuable insights, several limitations must be acknowledged. First, the study's contextual scope is limited to engineers and operators working in smart factories in a specific geographical region, which may not fully represent the broader industrial context. The findings may, therefore, be context-dependent, and caution should be exercised when generalizing them to other sectors or cultural settings. Additionally, the study relies on self-reported data from interviews, which may be influenced by social desirability bias or selective memory, thus affecting the accuracy of the accounts provided. Lastly, the sample size of 15 participants is relatively small, and while it allows for in-depth analysis, a larger sample could provide a broader understanding of the phenomenon across diverse settings and roles.

Prospective Statements for Future Research

The findings of this study offer several avenues for future research. One potential direction is to expand the research to explore how different cultural contexts influence workers' adaptation to automation and their experiences with human-robot interaction. It would also be valuable to investigate the long-term impact of automation on job satisfaction and career progression for workers in smart factories. Further studies could examine the role of leadership and organizational culture in supporting or hindering the successful integration of automation, as these factors may significantly influence the psychosocial adaptation of employees. Finally, longitudinal studies exploring the evolution of workers' identities over time as they transition through various roles in highly automated environments could provide a deeper understanding of the long-term implications of automation on professional self-concept and satisfaction.

CONCLUSION

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This study explored the experiences of engineers and operators as they adapt to the integration of robotic systems in smart factories. The findings highlight that the adaptation process involves both psychosocial and cognitive dimensions, such as emotional responses, changes in professional identity, and the development of trust in automation. These experiences were often overlooked in previous research that focused primarily on the technical aspects of automation. By applying a phenomenological approach, this study provides a deeper understanding of the human side of technological change, revealing the complexities of adapting to new roles in an increasingly automated workplace. The research addresses key gaps in the literature, emphasizing the need for a more holistic approach to human-robot collaboration that integrates both technical and emotional aspects. To make this transition more successful, it is recommended that companies implement targeted training programs that not only address technical skills but also focus on emotional resilience and trust-building with robotic systems. Organizations should establish clear communication channels about the role changes and the benefits of automation to reduce resistance and increase buy-in from employees. Policies could also be introduced to ensure continuous learning opportunities, such as regular upskilling workshops or mentorship programs, to support engineers and operators in adapting to new roles. Furthermore, leaders should be trained to actively support their teams during the adaptation process, providing emotional and psychological support to alleviate stress and anxiety associated with automation. Future research could expand this work by exploring the impact of organizational culture and leadership on workers' adaptation, offering further insights into how to support employees through the transition to automated systems.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article. All findings and interpretations presented in this study are based solely on the research data and are independent of any financial or personal relationships that could influence the research process.

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