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Sustainable healthcare futures: how digital leadership stimulates nurses' green creativity: a quasi-experimental study

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Abstract

Background In the context of increasing environmental consciousness, integrating sustainable practices in healthcare is essential. Nurses' green creativity, defined as their ability to generate innovative, eco-friendly solutions, is pivotal in this transformation. Digital leadership, which leverages technology to guide sustainable practices, plays a critical role in fostering this creativity among nurses.

Aim This study aimed to investigate the impact of digital leadership on enhancing nurses' green creativity and to evaluate the effectiveness of digital leadership strategies in promoting sustainability within healthcare settings. Research hypothesis: H1: Participation in a digital leadership program will lead to a significant enhancement in nurses' knowledge about digital leadership.H2: A digital leadership program will have a significantly positive impact on fostering nurses' green creativity.

Methods A quasi-experimental design was employed, involving 128 nurses randomly assigned to intervention and control groups. The intervention group participated in a digital leadership training program. Data were collected using a self-administered questionnaire, the Digital Leadership Competency Scale, and the Green Creativity Scale, before and after the intervention. Results: The mean knowledge score in the intervention group increased from 15.21 ± 4.22 pre-intervention to 44.29 ± 2.61 post-intervention ($p < 0.001$). For digital leadership competency, the mean score in the intervention group rose from 191.67 ± 20.43 to 552.14 ± 16.72 ($p < 0.001$). The mean score for green creativity in the intervention group significantly improved from 15.58 ± 1.68 to 42.31 ± 2.54 ($p < 0.001$).

Conclusion The study concluded that digital leadership programs significantly enhance nurses' green creativity. Integrating digital leadership into nursing practice can promote sustainability and innovation in healthcare settings.

Keywords Quality of health care, Sustainable development goals, Digital leadership, Digital health creativity, Green practices, Nursing, Environmental health

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Introduction

In this era of increasing environmental consciousness and the pressing need for sustainable healthcare and digital transformation, nurturing nurses' green creativity and embracing digital leadership strategies are crucial steps toward a more sustainable future. Green creativity refers to the generation of innovative, eco-friendly ideas, solutions, and practices that address environmental challenges and promote sustainability. By empowering nurses to become catalysts for change, healthcare organizations can enhance their environmental performance [1]. Nurses' green creativity refers to their ability to generate innovative ideas, solutions, and practices that address environmental challenges and promote sustainability within their healthcare settings [2, 3]. Combining clinical expertise with a deep understanding of ecological issues enables the development of new approaches that minimize environmental impact and optimize resource utilization. Nurses' green creativity includes actions that advocate for sustainable healthcare policies [4].

Digital leadership describes a social impact technique that uses modern communication technology and digital information to shape the behavior, thinking, feelings, and performance of individuals, organizations, and work groups [5]. Digital leadership is a concept that combines the principles of sustainability with the strategic use of digital technologies such as mobile devices, communications applications, the web, electronic platform tools, artificial intelligence, big data, and functional empowerment to bring about changes in organizational culture, mission, goals, and administrative processes [6].

More broadly, digital leadership refers to the strategic use of digital technologies, including communication platforms, data analytics, and collaborative tools, to guide, inspire, and enhance organizational performance across all sectors [6]. This leadership style drives efficiency, innovation, and data-driven decision-making. In the context of healthcare, digital leadership serves as a catalyst for promoting environmental sustainability. When combined with the principles of green creativity, digital leadership empowers nurses and healthcare professionals to develop innovative solutions to ecological challenges [7].

In the era of digital transformation, nurses can harness the power of technology to drive environmental sustainability initiatives [5]. Digital leadership includes utilizing digital communication platforms, data analytics, and collaborative tools to educate, engage, and empower nurses to embrace sustainable behaviors. Digital innovations that enhance the efficiency of healthcare delivery are encouraged [6]. The convergence of nurses' green creativity and digital leadership creates a powerful synergy that can propel sustainable change within the nursing profession [7]. By stimulating nurses' green creativity,

organizations can tap into their unique perspectives and insights to identify environmentally friendly solutions and drive innovation. Moreover, digital leaders provide nurses with tools and platforms to amplify their impact, collaborate with peers, and inspire others to adopt sustainable practices [8, 9].

As healthcare professionals, nurses are becoming increasingly aware of the need to incorporate sustainable practices into their daily routines. They understand that sustainable healthcare not only benefits the environment but also enhances patient outcomes and reduces healthcare costs [10]. Creativity is the process by which new ideas are formed, which leads to the development of new methods and the commencement of new actions. This process of transforming unique ideas into profitable and beneficial business practices is the basis of innovation in any organization [11].

Green creativity is described as "the development of new ideas about green products, green services, green processes, or green practices that are judged to be original, novel, and useful" [12]. The concept of green creativity emerged as a response to the growing recognition of the urgent need to address environmental issues such as climate change, resource depletion, pollution, and biodiversity loss [9, 13]. Traditional approaches and practices are often insufficient to address these complex problems, and new ways of thinking and acting are required [14]. Green creativity is critical for sustainable, green, and clean production, alongside producing distinctive green ideas that can lead to green innovation and production [2, 15]. It encourages individuals and organizations to question existing norms, challenge assumptions, and explore alternative solutions that prioritize environmental sustainability [16].

Nurses' green creativity encompasses a range of actions, such as implementing recycling programs, reducing medical waste, optimizing energy usage, promoting green procurement practices, and advocating for environmentally friendly policies within healthcare institutions [17]. In addition to these actions, nurses can engage in cross-disciplinary collaboration to develop sustainable healthcare systems. For instance, nurses can work closely with environmental engineers to design energy-efficient hospital infrastructure or collaborate with waste management teams to create more effective biomedical waste disposal strategies [16]. Furthermore, nurses play an essential role in educating patients and communities on sustainable healthcare practices, such as minimizing the environmental impact of home-based medical care [15]. The role of nurses is highlighted through green creativity in generating innovative ideas, solutions, and practices that address environmental challenges and promote sustainability within the healthcare sector. As frontline caregivers and advocates for patient

well-being, nurses have a unique opportunity to influence and drive positive changes in healthcare practices to minimize environmental impacts [14]. Given the rapid changes in the healthcare landscape and global environment, there is a growing need to find a leadership style that enables organizations to quickly adapt and stay competitive. Digital leadership has emerged as a viable approach, as it leverages digital information and communication technology to keep up with rapid developments [18].

This style of leadership revolves around utilizing digital tools and data to facilitate planning and decision-making and ultimately achieve high-performance results [18]. By embracing data-driven decision-making, fostering agility and collaboration, prioritizing customer centricity, promoting continuous learning and creativity, and enabling remote work, digital leaders can navigate the evolving healthcare organization landscape and maintain their competitive edge [19].

The importance of digital leadership is due to its strategic value in supporting and facilitating the administrative processes, decision-making, and overall functioning of individuals and institutions. It assists leaders in planning and enables the delivery of high-quality services with advanced technical capabilities [20, 21]. Digital leaders leverage technology to gain a competitive edge, optimize operations, make informed decisions, foster innovation, enhance customer experiences, possess technical expertise, and develop talent within their organizations [22, 23].

The healthcare industry grapples with the environmental impact of its practices, and nurses are uniquely positioned to drive positive change through their roles as frontline caregivers and influential leaders [22]. Digital platforms enable leaders to create online communities, social networks, and collaborative spaces where ideas can be shared, best practices can be disseminated, and collective action can be fostered. Leaders can use these platforms to engage stakeholders, raise awareness, and encourage participation in green initiatives [21, 23]. Green creativity and digital leadership are two interconnected concepts that hold immense potential for promoting sustainability and environmental stewardship within the profession [24, 25].

In recent years, digital leadership has been increasingly recognized as a key factor in driving transformation within healthcare systems. Studies have explored how digital leadership influences organizational effectiveness by enabling the integration of digital technologies into healthcare workflows, thus enhancing service delivery and patient outcomes. For example, Laukka et al. emphasized the importance of nurse leaders employing strategic thinking and vision to develop and implement digital solutions that promote both clinical and operational efficiency within healthcare settings [26].

Additionally, the relationship between digital leadership and creativity has been highlighted in other sectors. A study by Öngel found that digital leadership positively impacts individual creativity and employee performance across industries, emphasizing that leaders who effectively leverage digital tools foster innovation among their teams [27].

While research has extensively explored green transformational leadership and its role in fostering green creativity across various sectors, the specific integration of digital leadership into this domain remains underexplored. Unlike traditional leadership, which primarily focuses on personal and organizational influence, digital leadership leverages technological tools and data-driven decision-making to amplify sustainable practices. In the context of nursing, the rapid digitization of healthcare presents a unique opportunity to integrate digital leadership in promoting eco-friendly innovations, yet this relationship has not been fully examined in existing literature.

The current study fills this gap by evaluating how digital leadership directly influences nurses' green creativity, especially within healthcare settings where sustainability practices are urgently needed. By focusing on nurses, who are often at the forefront of patient care, this research highlights the transformative potential of digital leadership in stimulating environmentally conscious solutions, thereby contributing to both healthcare innovation and sustainability.

Methods
Aim
This study aimed to investigate the impact of digital leadership on fostering green creativity among nurses. Also, evaluate the effectiveness of digital leadership strategies in promoting sustainable practices within healthcare settings.

Research hypothesis
Hypothesis 1 (H1)
Participation in a digital leadership program will significantly enhance nurses' knowledge about digital leadership.

Hypothesis 2 (H2)
The digital leadership program will have a significant positive impact on fostering nurses' green creativity.

Design
A quasi-experimental design with pretest and posttest measures was used in this study, conducted from November 2023 to February 27, 2024.

Setting

The study was conducted in public university hospitals in Egypt, encompassing all departments and sections responsible for providing care to patients of varying ages with diverse medical and surgical conditions.

Sampling

To determine the necessary sample size, power analysis was conducted using G*Power software version 3.1.9.4, specifically for regression analysis [28]. The analysis was based on achieving 80% power, with an alpha level of 0.05, and assuming a moderate effect size (Cohen's $d = 0.5$) [29]. The sample size was 128 nurses after accounting for a 10% dropout rate.

Participants

The study employed a random sampling approach to assign participants to intervention and control groups, tailored to meet the study's objectives. Nurses were selected through a simple random sampling method to ensure equal representation from each hospital, based on the available lists of employed nurses. A total of 128 nurses were recruited and randomly allocated into the intervention group ($n = 64$) and the control group ($n = 64$). To ensure transparency and consistency in group assignments, randomization was conducted using a computer-generated random number sequence, generated by statistical software to eliminate any potential bias in the allocation process.

Eligibility criteria required participants to hold a bachelor's or master's degree and to have at least six months of professional experience. Exclusion criteria included failure to attend more than one session of the training program or prior participation in digital leadership training. All participants met the inclusion criteria, and none were excluded.

Tools for data collection

Three instruments were used to collect data for this study;

Table 1 Characteristics of the study participants

Variable	Intervention group	Control group
Age (year), mean ± SD	27.20 ± 3.05	26.65 ± 2.78
Experience (year), mean ± SD	4.03 ± 3.00	3.61 ± 2.75
Gender		
Male	36 (56.2%)	37 (57.8%)
Female	28 (43.8%)	27 (42.2%)
Educational background		
Bachelor	64 (100%)	64 (100%)
Current position		
Staff nurse	53 (82.8%)	55(% 85.9)
Head nurse	8 (12.5%)	6 (9.4%)
Supervisor	3 (4.7%)	3 (7.4%)

First tool: A self-administered questionnaire was utilized, which included two parts. The first part gathered nurses' demographic information through a questionnaire consisting of six items (Table 1). The second part contained knowledge-based questions designed to assess their knowledge before and after the digital leadership program. These questions were prepared by the researchers after reviewing the relevant literature [17, 22, 23]. The questionnaire included 50 multiple-choice questions, where each correct answer received one point, and each incorrect answer received zero points, making the total possible score 50. The reliability of this instrument was supported by a Cronbach's alpha score 0.76.

Second tool: The digital leadership competency scale was developed by Munsamy (30). Its aim is to measure and assess the competencies required for digital leadership. The framework consists of six main domains: embracing digital skills (21 items), leadership facilitating the digital drive (22 items), digital adaptiveness and resilience (13 items), cultivating a digital culture (14 items), digital skills (12 items), and digital competitiveness intelligence (11 items). The responses were measured on a seven-point Likert-type scale ranging from 1 = strongly disagree to 7 = strongly agree. The guidelines of Cohen (1988) for $\alpha \geq 0.70$ were used to determine the reliability of the scale [30].

Third tool: The Green Creativity Scale was developed by Jiang et al. (2021) and contains 16 items divided into 4 dimensions: green creative motivation (4 items), green creative thinking (4 items), green creative behavior (4 items), and green creative outcome (4 items). The composite reliability values of the four latent variables ranged from 0.76 to 0.80. Participants were requested to rate the items on a 3-point scale from 1 (strongly disagree), 2 (neutral), and 3 (strongly agree) [17].

Intervention

This program aimed to enhance the digital leadership skills of nurses by providing comprehensive, well-structured training and ensuring that the educational content was both accessible and relevant to their roles. At the beginning of the study, the researchers explained the purpose of the study, the necessity of participation, and the general topics of the training sessions. The assessment of participants' digital leadership and green creativity in the two groups occurred both before and one week after the intervention. Three tools were distributed: a self-administered questionnaire, the Digital Leadership Competency Scale, and the Green Creativity Scale for nurses. Participants were allotted one hour to complete the tools.

The researchers-controlled information transfer between the intervention and control groups by conducting separate sessions and instructing participants not to share details about the course with each other.

The training was delivered over 10 sessions, each lasting 60 min, held twice per week over a period of two months and two weeks. The sessions were conducted within hospital premises to enhance engagement, accessibility, collaboration, and feedback. The program was offered free of charge upon successful completion. Program directors utilized various instructional methods, including lectures, demonstrations, question-and-answer sessions, PowerPoint presentations, group discussions, video presentations, case reports, and scenarios. Additionally, members of the intervention group were granted offline access to program materials, including recorded videos and audio files from the course. The topics covered in the program are detailed in Table 2. While the intervention group had access to educational materials, the control group did not receive such instructional content.

The training session's content was created and formulated by drawing inspiration and insights from the relevant literature [4, 10, 17, 20, 22, 30, 31]. The training sessions included the following topics: digital transformation in healthcare, healthcare technology management, information governance and data management, health informatnagement, health informatnagement, health informatnagement, health information systems, telehealth, telenursing, and remote patient monitoring; health applications; digital communication and collaboration; digital leadership competencies; data-driven decision-making; and integrating green creativity into digital leadership. Material presentations were sent to all participants after the completion of every session. A post-test was conducted one week after the completion of the training using the same tools as the pre-test to assess the impact of the program, see details of training session in Table 2.

Statistical analysis

For analyzing the applied data, the data was thoroughly statistically analyzed using SPSS Version 26. The statistical analysis in this study involved the use of various statistical tools to examine the effects of digital leadership on nurses' green creativity. Descriptive statistics, such as means and standard deviations, were calculated to summarize the data. Paired t-tests were conducted to compare the pre- and post-intervention scores within groups, while independent sample t-tests were used to compare the intervention and control groups. Statistical significance was determined using p-values (e.g., $p < 0.05$), while Cohen's d was reported as an effect size to illustrate the magnitude of the intervention's impact. The thresholds for interpreting Cohen's d are commonly: 0.2 = small effect, 0.5 = medium effect and 0.8 = large effect. Additionally, 95% confidence intervals were calculated to provide a range of values within which the true effect is expected to fall, enhancing the interpretation of the

Table 2 Educational content related to the digital leadership program (intervention group)

Session 1	Digital transformation in healthcare	– Definition and scope of digital transformation. – The role of technology in reshaping healthcare processes and patient care. – Steps for healthcare transformation – Key Drivers of Digital Transformation – Benefits of Digital Transformation – Challenges and barriers
Session 2	Healthcare technology management	– Definition of healthcare technology management – Importance of healthcare technology management – Healthcare technology ecosystem – Key components of healthcare technology management
Session 3	Information Governance and Data Management	– Definition of information governance and its role in healthcare – Principles of Information Governance – The importance of data in healthcare – Challenges in Data Management – 7 Tips for Success with Information Governance – Components of Information Governance – Data security and privacy
Session 4	Health information systems	– Definition of health information system – Components of the health information system – Benefits of the health information system – Challenges and barriers
Session 5	Telehealth, telenursing, and remote patient monitoring	– Definition of telehealth – Telehealth vs. Telemedicine – Benefits of Telehealth and Tele-Nursing – Components of Telehealth – Remote Patient Monitoring (RPM) – Telehealth in Chronic Disease Management
Session 6	Health apps	– Definition of health apps – Benefits and potential impact on healthcare delivery – Types of Health Apps – Benefits of Health Apps – Fitness and Exercise Apps – Telehealth and Telemedicine Apps
Session 7	Digital communication and collaboration	– Definition of digital communication and collaboration – Elements of collaboration – Communication Technologies – Benefits of Digital Communication – Challenges in Healthcare Communication
Session 8	Digital leadership competencies	– Definition of digital leadership – Digital Leadership Competency Framework – Digital Literacy – Digital maturity – Strategies for Effective Digital Leadership

Table 2 (continued)

Ses-sion 9	Data-driven decision-making	– Definition of data-driven decision-making – Power of data in healthcare – Key components of data-driven decision-making – Types of healthcare data – Data analytics and tools – Data security and privacy
Ses-sion 10	Integrating green creativity into digital leadership	– Definition of green creativity – Key components of green creativity – Examples of green digital initiatives – Green creativity in telehealth

results' precision. The results showed statistically significant improvements in both knowledge and green creativity scores for the intervention group post-intervention, with large effect sizes (Cohen's d ≈ 0.98), indicating a substantial impact of the digital leadership program.

Handling of missing data and dropouts
In this study, missing data due to dropout or incomplete responses were handled using listwise deletion, where participants with missing values for key variables were excluded from the final analysis. This approach was considered appropriate due to the low percentage of missing data (< 5%), resulting in the deletion of 3 cases. Additionally, dropouts were carefully monitored during the intervention phase. A total of 8 nurses dropped out, and the reasons for their withdrawal were documented to maintain transparency. The final analysis was conducted on participants who completed both the pre- and post-intervention assessments.

Results
The mean age of the participants in the intervention group was 28.46 years, with a standard deviation (SD) of 3.22, while the control group had a slightly lower mean age of 28.07 years (SD = 3.25). The mean years of experience in the intervention group were 5.33 years, with an SD of 3.26, compared to the control group, which had a mean of 4.94 years (SD = 3.19). In terms of gender distribution, 56.2% of the intervention group were male, and 43.8% were female, while the control group had a similar distribution with 57.8% male and 42.2% female participants. The distribution across current positions revealed that 82.8% of the intervention group were staff nurses, 12.5% were head nurses, and 4.7% were supervisors, while in the control group, 85.9% were staff nurses, 9.4% were head nurses, and 7.4% were supervisors (Table 1).

The findings of the study showed that the mean knowledge score for the intervention group was 15.21 ± 4.22, and for the control group, it was 15.37 ± 4.09. After the intervention, the respective scores were 44.29 ± 2.61 for the intervention group and 17.69 ± 3.76 for the control

group. Within-group differences: both groups showed significant improvement (Paired t-test, $p < 0.001$) with large and small effect sizes (Cohen's d = 0.98 for intervention, 0.38 for control), respectively. According to the digital leadership competency scale, the mean score for the intervention group was 191.67 ± 20.43, while the control group had a mean score of 187.55 ± 16.27 before the digital leadership program. After the intervention, the intervention group's mean score increased to 552.14 ± 16.72, whereas the control group's mean score changed to 189.87 ± 13.79. The within-group differences for the intervention and control groups were 360.47 and 2.33, respectively. The effect size for the intervention group is 0.99, suggesting a substantial impact. The paired t-test for within-group differences yielded a value of 100.55 with a p-value of < 0.001, indicating statistical significance. The intervention group had a mean score of 15.58 ± 1.68, and the control group had a mean score of 16.53 ± 1.64 before the intervention. Post-intervention, the intervention group's mean score of green creativity increased to 42.31 ± 2.54, while the control group's mean score changed to 17.98 ± 2.09. The within-group differences for the intervention and control groups were 26.73 and 1.45, respectively. The effect size for the intervention group is 0.98, indicating a substantial impact. The paired t-test for within-group differences presented a value of 71.07 with a p-value of < 0.001, revealing statistical significance (Table 3).

Overall, the results of the study indicate significant improvements in participants' perception about digital leadership dimensions for the intervention group, highlighting the effectiveness of the digital leadership program. In contrast, the control group showed either non-significant changes or smaller improvements in these dimensions. P-values less than 0.05 suggested statistical significance in the observed differences (Table 4).

As observed, the results highlight that the digital leadership program had a significant positive impact on the perceived green creativity dimensions in the intervention group, leading to substantial improvements in motivation, thinking, behavior, and outcomes. In the control group, while there were improvements in some dimensions, the changes were generally smaller or non-significant. P-values less than 0.05 indicated statistical significance in the observed differences between the groups (Table 5).

Discussion
The statistical findings of the study revealed that the digital leadership program had a significant positive impact on the perceived green creativity dimensions in the intervention group (p-value < 0.001), leading to substantial improvements in self-reported motivation, thinking, behavior, and outcomes. However, these improvements

Table 3 Comparison of pre- and post-intervention scores for control and intervention groups

Variable	Time	Pre-intervention	Post-intervention	Mean differences	Effect size (Cohen d)	Paired t test	*p*
	Groups	Mean ± SD	Mean ± SD				
Knowledge	Intervention	15.21 ± 4.22	44.29 ± 2.61	29.08	0.98	47.26	<0.001
	Control	15.37 ± 4.09	17.69 ± 3.76	2.31	0.38	3.29	0.002
	t test	2.12	46.48				
	P	0.832	<0.001				
	Effect size (Cohen d)	0.019	0.97				
Digital leadership competency scale	Intervention	191.67 ± 20.43	552.14 ± 16.72	360.47	0.99	100.55	<0.001
	Control	187.55 ± 16.27	189.87 ± 13.79	2.33	0.076	2.951	0.004
	t test	1.26	133.71				
	P	0.209	<0.001				
	Effect size (Cohen d)	0.11	0.99				
Green creativity	Intervention	15.58 ± 1.68	42.31 ± 2.54	26.73	0.98	71.07	<0.001
	Control	16.53 ± 1.64	17.98 ± 2.09	1.45	0.36	4.27	<0.001
	t test	2.877	59.12				
	P	0.084	<0.001				
	Effect size (Cohen d)	0.27	0.98				

Significant if *P* value < 0.05

Table 4 Comparison of mean scores across digital leadership dimensions pre- and post-intervention

Group time of intervention dimensions	Intervention		Control	
	Pre Mean ± SD	Post Mean ± SD	Pre Mean ± SD	Post Mean ± SD
Embracing digital	34.91 ± 7.52	119.25 ± 8.72	33.09 ± 6.76	32.50 ± 6.14
P value	0.000		0.174	
Leadership facilitating the digital drive.	37.61 ± 6.93	130.66 ± 8.90	35.72 ± 6.12	35.89 ± 4.95
P value	<0.001		0.591	
Digital adaptiveness and resilience	33.76 ± 5.47	80.64 ± 4.74	33.53 ± 4.35	33.45 ± 3.84
P value	<0.001		0.826	
Digital skills	27.01 ± 5.55	71.73 ± 6.51	26.93 ± 4.98	28.37 ± 4.41
P value	<0.001		<0.001	
Cultivating a digital culture	32.73 ± 5.47	81.42 ± 5.19	32.04 ± 4.78	31.79 ± 4.70
P value	<0.001		0.441	
Digital competitive intelligence	25.64 ± 5.17	68.44 ± 5.89	26.22 ± 4.29	27.86 ± 4.17
P value	<0.001		<0.001	

Significant if *P* value < 0.05

Table 5 Comparison of mean scores across green creativity dimensions pre- and after-intervention

Group time of intervention dimensions	Intervention Before After		Control Before After	
	Mean ± SD Mean ± SD		Mean ± SD Mean ± SD	
Green Creative Motivation	3.98 ± 0.882	10.59 ± 1.03	4.09 ± 0.885	4.59 ± 1.18
P value	<0.001		0.011	
Green Creative Thinking	4.03 ± 0.942	10.72 ± 1.43	3.86 ± 0.833	4.47 ± 1.08
P value	<0.001		0.001	
Green creative behavior	3.75 ± 0.796	10.47 ± 1.31	4.28 ± 0.825	4.42 ± 0.956
P value	<0.001		0.355	
Green Creative Outcome	3.812 ± 0.833	10.53 ± 1.14	4.29 ± 0.659	4.50 ± 1.02
P value	<0.001		0.150	

Significant if *P* value < 0.05

reflect the participants' perceptions rather than objective evaluations of practice. In the control group, while there were significant improvements in some dimensions, the changes were generally smaller or non-significant. This suggests that the digital leadership awareness sessions played a crucial role in driving the participants' perceived

positive changes in green creativity dimensions. Further research involving direct observation would be needed to validate these findings.

The results of other studies were consistent with our findings [9, 29, 30] For example, a study was conducted in Nigeria. aiming at exploring green talent management

and turnover intention: The roles of leader STARA competence and digital task interdependence demonstrated that leader advances in smart technology, artificial intelligence, robotics, algorithms (STARA), and digital task interdependence, such as digitalization, organizational leaders have a positive impact on developing and retaining staff talent to address global climate change and organizational sustainability with p values (0.000) [29]. Additionally, Khaw et al. [33] in Switzerland indicated that digital leadership has a positive impact on sustainable performance.

The results of the present study indicated that the mean knowledge score for the intervention group was 15.21 ± 4.22, and for the control group, it was 15.37 ± 4.09 after the intervention, the respective scores were 44.29 ± 2.61 for the intervention group and 17.69 ± 3.76 for the control group. The findings of the study suggested that there was a significant improvement in knowledge scores for both the intervention group and the control group after the intervention.

These findings indicated that the intervention was effective at enhancing nurses' knowledge. The results obtained were consistent with those of several other studies [29, 34, 35] that highlighted the importance of digital leadership programs for stimulating employees' green creativity. Furthermore, the results of the present study are consistent with those of the study by Ebrahim et al. [35] which was conducted in Egypt and reported higher mean scores for nursing students' knowledge, attitudes, and behaviors toward sustainability development post-intervention in the study group. There was a highly significant difference between the study and control groups after the educational intervention ($p \le 0.05$).

Regarding digital leadership competency, the present study revealed that there was a significant increase in the mean score for the intervention group (552.14 ± 16.72) compared to a minimal change in the control group (189.87 ± 13.79) after the intervention. The researcher would likely interpret these results as evidence supporting the effectiveness of the digital leadership program in enhancing digital leadership competencies that stimulate nurses' green creativity. The results of the present study are in line with the study by Shin et al. [36], in South Korea who revealed that digital leadership has a positive effect on increasing employees' digital capabilities and improving their digital culture.

According to our findings on green creativity, after the intervention, there was a substantial increase in the mean score in the intervention group (42.31 ± 2.54) compared to a smaller change in the control group (17.98 ± 2.09) after the intervention of the digital leadership program. From the researchers' point of view, our findings suggested that the green creativity intervention had a noteworthy effect on the intervention group's scores. The

present study results are in agreement with those of other studies [37, 38] for example a study by Mollah et al. [38] in South Korea showed that digital leadership was positively and significantly correlated with sustainable organizational performance ($r = 0.678$, $p < 0.01$).

Digital leadership among healthcare providers is the ability of leaders within the healthcare sector to effectively navigate, leverage, and drive digital transformation in healthcare settings. The digital leadership dimensions in healthcare include embracing digital culture, facilitating digital drive, providing digital adaptiveness and resilience, providing digital skills, cultivating a digital culture, and providing digital competitive intelligence [39]. The present study revealed significant improvements in digital leadership dimensions within the intervention group highlighting the effectiveness of the digital leadership program. In contrast, the control group showed either non-significant changes or smaller improvements in these dimensions. From the researcher's perspective, the findings suggested that the digital leadership program was successful at bringing about meaningful changes in the skills and abilities of nurses in the intervention group.

The obtained results were consistent with those of other studies [32, 34, 35] that stated the importance of digital leadership programs for improving digital leadership dimensions among study participants. In addition, the findings of the present study were in line with those of the study by Acharya et al. [21] which was conducted in the United Kingdom and reported that the digital leadership program had a broader impact on national digital priorities, facilitating communication between organizations and improving the efficiency of the national digital infrastructure.

Green creativity is the ability to generate innovative ideas, solutions, and products that are environmentally sustainable and promote a more ecologically friendly way of living; this ability involves four dimensions: green creative motivation, green creative thinking, green creative behavior, and green creative outcome [17]. The findings of the present study illustrated that the digital leadership program had a significant positive impact on the green creativity dimensions of motivation, thinking, behavior, and outcomes after the intervention of the program, which reflects the effectiveness of the digital leadership program.

Consistent with the findings of the present study, in Korea and China, Niu et al. [32] asserted that digital leadership had a positive effect on both countries and that environmental, social, and governance management (ESG Management) had a positive effect on organizational innovation and sustainability. The results of other studies have suggested that digital leadership stimulates green creativity dimensions among study subjects [14, 36, 39]. Moreover, the current study results were supported

by Zahrani [40] which was conducted in Saudi Arabia and found that top management and human resource management had a positive impact on team creativity and green practices with mediating roles in organizational sustainability.

The findings of this study offer significant practical implications for nursing practice, particularly in promoting sustainability. Digital leadership has the potential to reshape how nursing teams integrate sustainable practices within healthcare settings. By leveraging digital tools and data-driven decision-making, nurse leaders can drive initiatives that minimize environmental impact, such as reducing medical waste, optimizing resource utilization, and implementing energy-efficient practices. That supported by studies as [37, 38].

Furthermore, digital platforms allow nurse leaders to foster collaboration and innovation among teams by enabling the sharing of best practices and sustainability strategies in real time. These tools also empower nurses to take proactive roles in environmental advocacy, not only within healthcare facilities but also in patient education, encouraging sustainable health practices at home.

Incorporating digital leadership into nursing curricula and continuing professional development programs can equip future nurse leaders with the competencies needed to champion sustainability. As healthcare continues to embrace digital transformation, nurses empowered by digital leadership will play a pivotal role in advancing both patient care and ecological responsibility, aligning healthcare operations with broader global sustainability goals. This is supported by numerous studies, including [38–40].

Conclusion
The study concluded that digital leadership programs have a significant positive impact on stimulating nurses' green creativity. The intervention led to substantial improvements in various dimensions of green creativity, such as motivation, thinking, behavior, and outcomes. However, it is important to note that these findings are based on the self-reported perceptions of the participants, gathered through a self-administered questionnaire. The assessment of behavior and outcomes, in particular, was not based on direct observation but on the participants' own perceptions. Future research incorporating observational methods would be beneficial to confirm the actual impact on behavior and tangible results. These findings underscore the potential of integrating digital leadership into nursing practice to promote sustainability and innovation in healthcare settings.

Implications for practice
Healthcare organizations and policymakers should prioritize incorporating digital leadership training into professional development and nursing education programs. Such initiatives can enhance nurses' ability to adapt to the rapidly evolving healthcare environment and spearhead environmentally sustainable practices. By investing in digital leadership, healthcare organizations can empower nurses to generate innovative, eco-friendly solutions, thereby contributing to more sustainable healthcare systems.

Limitations of the study
The study's quasi-experimental design limits the ability to establish causality between digital leadership training and the observed improvements in green creativity. Our study relied heavily on self-reported data, which is subject to several biases, including social desirability bias, where participants may provide responses they believe are favorable or expected, rather than reflecting their true behaviors or attitudes. This can inflate the perceived effectiveness of the intervention. Finally, the study was conducted in a specific geographic and institutional context, potentially limiting the generalizability of the findings to other settings. Further research involving randomized controlled trials and objective measures, such as direct observation of behavior, would strengthen the conclusions and provide a more robust assessment of digital leadership's effectiveness.

Author contributions
"Conceptualization", Hossam Ali Ismail, Mohamed Hashem Kotp, Hasan Ahmed Awad, Aliaa EzzEldin Abd-Elmoaty, Mohamed Ahmed Aly; Methodology, Salwa sayed, Ahmad Ahmeda, Ahmed Hendy; validation, Abdelaziz Hendy and Maha Suwailem Shuaib Alshammari; formal analysis, Ahmed hendy and ahmed ahmeda; writing—original draft preparation, Hossam Ali Ismail, Mohamed Hashem Kotp, Hasan Ahmed Awad, Aliaa EzzEldin Abd-Elmoaty, Mohamed Ahmed Aly, sally mohammed; editing and Ahmed Hendy; statistical analysis. Salwa sayed; writing—review and editing, Hossam Ali Ismail, Mohamed Hashem Kotp, Hasan Ahmed Awad, Aliaa EzzEldin Abd-Elmoaty, Mohamed Ahmed Aly, sally mohammed; visualization, Aliaa EzzEldin Abd-Elmoaty, Mohamed Ahmed Aly.; project administration, Ahmed hendy; All the authors have read and agreed to the published version of the manuscript."

Ismail *et al. BMC Nursing*   (2025) 24:251

Page 10 of 11

Data availability
Data is provided within the manuscript or supplementary information files.

Declarations

Ethical aproval and consent to participate
The study received ethical approval from the Ethics Committee of the Faculty of Nursing at Helwan University, Egypt (ID.36, date: 03.10.2023). All participants were provided with detailed information about the study's purpose, procedures, potential risks, and benefits. Nurses who volunteered to participate gave their written informed consent at least two weeks prior to the intervention. The consent process ensured that participation was entirely voluntary, with participants informed that they could withdraw from the study at any time without any repercussions on their professional standing. In addition to obtaining informed consent from the participants, the study adhered to ethical standards, ensuring confidentiality and data protection throughout the research process. Institutional approval was also granted by the participating hospitals, ensuring the study complied with local ethical regulations. The ethical approval followed the guidelines outlined by institutional ethics boards for clinical research involving human participants, ensuring that the study upheld the highest standards of research ethics.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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