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Enhancing operational competency in desalination plants: A virtual reality-based training model for entry-level technicians

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Abstract

The ongoing water crises worldwide have prompted the demand for trained desalination technicians to address water scarcity concerns. Consequently, focusing on this problem, the current study intends to propose a Virtual Reality (VR) training program for the skill development of novice desalination technicians and examine and compare its effectiveness for enhancing the practical competence of new trainees against those of traditional training approaches. A quasi-experimental research design with a triangulation approach was employed, and 30 trainees were recruited for the study. The participants were divided into two groups: control (traditional training) and experimental (VR training), each encompassing 15 trainees. The VR module was designed to simulate reverse osmosis (RO) operations, and participants' skills were assessed pre-training and post-training using checklists, performance scores, and surveys. The findings revealed significant improvements in the VR group compared to the control group, showing that their performance scores went up by 19.7 points, in contrast to the traditional group's 9.8 points. Furthermore, the VR group demonstrated 34% higher accuracy, 28.5% improvement in task completion time, and 42.3% improvement in procedural compliance compared to those trained with traditional methods. Additionally, the experimental group also completed a survey to report their satisfaction and perceptions regarding distinct aspects of the VR module and indicated that participants found the system highly realistic and interactive. Overall, the results specified that VR is a safer, more effective, and more engaging way of training desalination technicians and that the technology has promise for advancing skill acquisition and operations in the water industry.

Keywords: Desalination, Technician training, Operational competency, Reverse osmosis (RO), Skill enhancement, Virtual reality (VR), Water treatment.

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1. Introduction

Water scarcity has become a major issue, afflicting billions across the world, and is continually worsening owing to climate change, industries, and a growing population, making it essential to discover innovations for obtaining fresh water [1, 2]. According to the WHO [3] over 2 billion people reside in water-stressed countries, and by the year 2050, every three out of four people worldwide are expected to encounter drought impacts [4, 5]. In this regard, seawater desalination has emerged as one of the critical resolutions to cope with water scarcity challenges [5]. Desalination (the process of desalting seawater) is regarded as one of the imperative solutions, particularly in warmer and drier regions and cities with a lack of water resources [6, 7]. Therefore, the technicians who operate these desalination plants are important since their skills have a direct impact on the performance of the plant, the quality of water, the cost of operations, and overall safety [8]. Traditional training approaches for desalination technicians face significant limitations, creating a need for innovative solutions like Virtual Reality (VR) [9]. This study aims to develop and evaluate a VR-based training program for novice desalination technicians and compare its effectiveness against traditional methods.

1.1. Research Objectives

- To develop and evaluate a VR-based training module that simulates major technical procedures involved in the desalination process for entry-level operators.
- To measure pre- and post-VR training changes in the performance of trainees.
- To examine trainees' perceptions regarding the VR training experience, including the challenges and patterns of behavior.

1.2. Research Questions

RQ1. Does virtual reality training enhance the technical competencies of trainees in desalination operations?
RQ2. What are the trainees' perceptions regarding the effectiveness of distinct aspects of VR-based instructions (i.e., usability, engagement, etc.)?
RQ3. What challenges and patterns of behavior occur in VR training?

2. Literature Review

Desalination technicians are in charge of monitoring complex setups, performing routine maintenance services, troubleshooting, and attending to emergencies [10, 11] each activity requires high levels of technical expertise. Advanced desalination techniques like reverse osmosis (RO), forward osmosis (FO), and multi-effect distillation (MED) are quite intricate, characterized by thorough chemical procedures, sophisticated machines, and massive control systems [12-14]. Hence, it can be asserted that for operating desalination facilities effectively and securely and ensuring their proper functioning, there is a need for highly skilled and experienced personnel who have received practical training in addition to mastering relevant concepts.

2.1. Traditional Training Methods and Their Limitations

Traditionally, training the technicians in water treatment fields, including desalination, was majorly done by providing On-the-Job Training (OJT), printed Standard Operating Procedures (SOPs) and manuals, and being trained by supervisors who demonstrated how to do particular tasks [15, 16]. However, these approaches were costly, dangerous, and difficult to remember for learners [17]. Besides, only theoretical knowledge rarely prepares workers for operating complex plants and encountering complex working scenarios, leading to a significant number of operators being ill-prepared to deal with actual operating challenges [18]. On the contrary, direct handling of actual equipment by new trainees may also result in safety concerns and damage, and the errors might prevent the plant from operating, harm the expensive machines, or even induce potential hazards [19]. Hence, overall it was noted that although theoretical knowledge does not transform into real skills without practice [20, 21] exposing novice learners to actual working equipment also poses safety issues for both the trainees and the plant, since the mistakes made could lead to significant delays or destroying of equipment [22]. Therefore, Virtual Reality (VR) technology delivers a middle ground in this paradigm by proposing a complementary solution to combine practical execution with a risk-free horizon to ascertain the provision of high-quality training within a safe, inexpensive, and extendable learning environment [9, 23, 24].

2.2. Virtual Reality as an Innovative Training Tool

Attributed to its immersive, interactive, and safe learning environments, VR has made it possible for trainees to perform complex operations, develop problem-solving skills, and become accustomed to the working environment without the danger and obstacles of classical training [25, 26]. The benefits of the use of VR for technical training are widely acknowledged in previous research in high-risk industries requiring high levels of skill and safety awareness, such as aviation [27], healthcare [28, 29] and energy sectors [30, 31]. Researchers have revealed that VR facilitates enhanced learner engagement, spatial perception, complex systems comprehension, and stepwise task practice with instant feedback, contributing to better skills retention, equipment maintenance, and improved performance in real-world settings [32-34]. Within the desalination training sector, VR has the potential to offer the development of secure, hazard-free, realistic environments to facilitate interactive learning, augmenting understanding, providing immediate feedback and accurate performance analysis, and thus, enabling better comprehension of operation systems for novice technicians all within an upgraded and highly efficacious training space [35]. However, although studies have examined the integration of advanced technologies and processes in desalination, such as using Artificial Intelligence (AI) [36] and adopting sustainable practices [6, 37] there is a dearth of research exploring the use of VR technology in the training context. This reveals significant research gaps in relation to empirical knowledge, technological integration, and practical evidence on the topic of VR integration in the desalination training paradigm.

2.3. Theoretical Framework

2.3.1. Constructivist Learning Theory

This study is grounded in Constructivist Learning Theory, which states that the learners construct their understanding and knowledge through experience and thought [38, 39] and is one of the significant theories for the current study. Different from the conventional teaching approaches where learners are considered to receive information passively, constructivism adopts the approach of creating knowledge through interaction with the environment and social communication [40, 41]. In the context of the current study, the VR environment is intended to be supported by providing an interactive and realistic environment where learners can actively explore, handle objects, make decisions, and see the consequences of their actions [42]. The VR module for the desalination plant technicians was for creating a hands-on, contextual learning scenario and enriching them on complex systems and procedures where they will be actually interacting with virtual equipment and processes, gaining better cognitive ownership and better-developed skills [43].

2.3.2. Experiential Learning Theory

Another theory that explains further how VR can be used to enhance learning, particularly practical skills, is David Kolb's Experiential Learning Theory (ELT) [44, 45]. The ELT approach emphasizes "learning by doing" and considers learning as a cycle that has four stages. Concrete Experience (CE) – Having an experience, Reflective Observation (RO) – Thinking about the experience, Abstract Conceptualization (AC) – Getting insights from the experience, and Active Experimentation (AE) – Practicing what you learn [46, 47]. The VR training for desalination technicians was planned to follow this cycle: trainees would gain experience by carrying out tasks (such as a start-up sequence, and fault diagnostics) in the simulated plant; trainees would demonstrate and reflect on their performance through feedback, scenario replays, and debriefings; trainees could develop mental models of plant operations and troubleshooting based on that reflection; and then, trainees could apply that knowledge to other scenarios or repeat tasks to refine those skills and experience within the safe, reproducible VR environment [48, 49]. This was a necessary cycle to convert theoretical knowledge into practical skills.

2.3.3. Technology Acceptance Model

Finally, in order to interpret and forecast acceptance and effective use of the developed VR training module by the intended end users, the base-level desalination plant technicians, this study used the Technology Acceptance Model (TAM) [50]. TAM was a practically validated information systems theory that theorized how a user came to accept and use technology [51]. The model recommended that two beliefs constituted the major ones that influenced one's behavioral intention to use a system. Perceived usefulness (PU) is set by "the degree to which a person believes that using a particular system would enhance his or her job performance" [52, 53] which is the degree to which a person believes, based on a particular system, that he/she would not have. This study examined these constructs through evaluations, questionnaires and user feedback after experiencing the virtual reality module to determine factors related to the technicians' willingness to adopt virtual reality training. Positive perceptions of both usefulness (e.g., they perceived VR to enhance their ability to learn job-related tasks or helped them complete tasks more safely) and ease of use (e.g., they felt that the VR interface was straightforward and not too complicated) were crucial to implementing and integrating the virtual reality training model into existing programs [54].

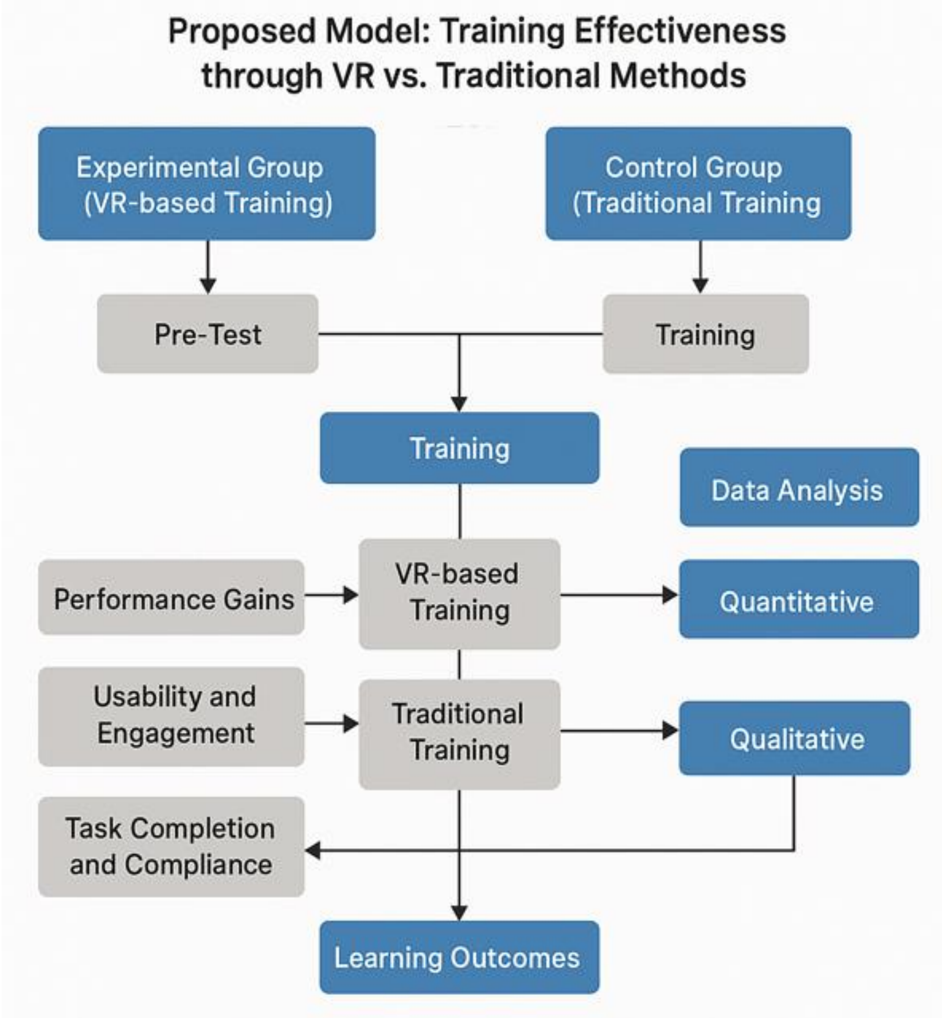

Figure 1.
Effectiveness of VR Training vs. Traditional Methods.

3. Methodology

The current study has employed a quasi-experimental pretest-posttest research design incorporating a triangulation approach to examine the effectiveness of virtual reality (VR) based training compared to the traditional mode of teaching for the desalination process. This research design was selected because, as quasi-experiments allow estimating causality between intervention and outcome, it appeared to be best aligned with the aims of the current study [55, 56]. The study's quantitative component aimed to quantify and compare changes in performance between both groups at baseline and following the intervention, while the qualitative component aimed to capture their perceptions and learning experiences with the VR system. Participants to the study were recruited using a non-randomized, purposive sampling strategy, and 30 entry-level trainees from the desalination industry participated as study participants. The trainees were evenly divided into two groups of 15 participants. The first group (control group) was taught through traditional teaching methods, and the second group (experimental group) was taught using a virtual reality (VR) training module that was invented in this study (and discussed in the next section). Before assigning the groups, all participants were asked if any of them, specifically within the experimental group, had suffered from motion sickness, eye strain, or other health issues that may impact their participation within this research study, as well as their safety. Both groups were taught over a duration of three weeks, with training provided across three sessions (30 minutes per sessions), spaced weeks apart, which allowed time for the participants to engage with the study content.

3.1. VR-Based Training Module

The VR training module was created using a Unity 3D software package and was compatible with Oculus Rift/Meta Quest or HTC Vive headsets. The model simulated the operation of a reverse osmosis (RO) system so that users could exercise activities, including changing filters, calibrating sensors, and controlling pump pressure. RO technique was chosen since it is currently the most extensively adopted desalination technology across the globe, given its cost-effectiveness, high energy efficiency, and ability to produce potable water from seawater with high purity [57-59]. Thus, the training model was designed on the RO system to align with current industry trends, demands, and operational requirements. Figure 2 indicates the steps involved in the simulated reverse osmosis (RO) process within the VR module.

Figure 2.
Steps Involved in Reverse Osmosis (RO) Process.

Operating the RO equipment, handling regular upkeep tasks, and addressing situations such as when the power cuts off were part of the trainees' work. Imitation of real equipment through 3D technology was intended to improve students' learning experiences. In the module, trainees were required to take part in simulations with helpful information and instant feedback to guide them on the right actions and responses. Figure 3 presents the technician's avatar's view in the VR training module during the filter replacement task.

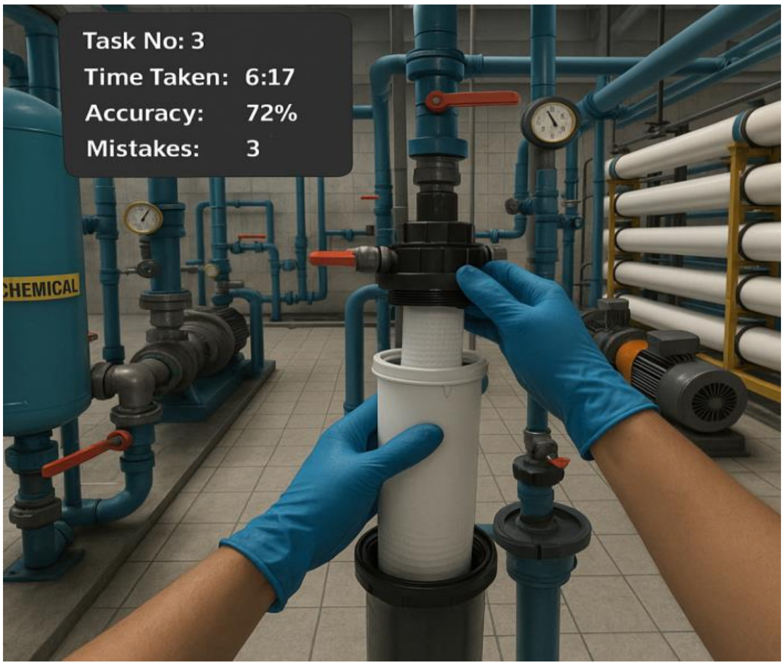

Figure 3.
Technician's Avatar's View in VR Training Module during the Filter Replacement Task.

As seen in Figure 3, trainers used the integrated management system to track user progress, including keeping track of how each task is done, showing the time taken, the accuracy achieved, and how many mistakes were made, making the assessment more objective. The panel continually displayed the information, though the position kept changing with participants' movements, to offer a track of each activity to the trainees and hence provide them with instant feedback on their overall progress so that they can identify their mistakes and try to achieve higher accuracy within a more constrained time frame. The simulation was intended to replicate actual plant layouts and strictly adhered to standard operating procedures (SOPs) to increase the realness of the environment. Scenario-based interactions were included to let the participants act upon emergency conditions, such as system shutdowns, as illustrated in Figure 4.

Figure 4.
Shutdown Emergency Scenario Displayed in the VR Module.

The emergency scenarios urged the trainees to make quick decisions within a confined time duration, and the timer was displayed in the top right panel of the screen, showing the time left to respond in seconds. Overall, by exploring different aspects of the module, the evaluation was done to discover how it affects workers' competence and quickens the training process at desalination plants.

3.2. Data Collection Tools

Different data collection tools were used to measure the pre-post training performance as well as participants' perceptions. The training coaches first evaluated the skills of both groups before the initiation of the training process. A skill-based checklist was used to test trainees' performance before and after the training in relation to their ability to perform tasks, including filter replacement, sensor calibration, and controlling pump pressure. Similarly, a metric-based evaluation was also conducted before and after the training to test participants' task completion accuracy, time duration, and overall procedural compliance. Apart from the pre-post tests, a 5-point Likert scale-based satisfaction survey was conducted with participants from the experimental group to assess their perceptions regarding different aspects of VR-based instructions, including usability, engagement, Clarity, confidence boost, and realism. Participants rated their level of satisfaction on a scale from 1 to 5 for each dimension. Lastly, short interview sessions (20 minutes each) were conducted with each participant from the experimental group to explore their perceptions and experience regarding the VR module, including the challenges and behavioral patterns encountered.

3.3. Data Analysis

SPSS Statistics V27 was used as the data analysis tool, and descriptive analyses were conducted to quantitatively analyze the data, involving means and standard deviations, to describe the results before and after the training. Inferential statistics were employed using a paired t-test to examine significant differences in skill improvement between the two research groups, based on the assumption of normal data distribution. For qualitative data, a thematic analysis approach was used to identify the core themes capturing trainees' perceptions and learning experiences with the VR module. Braun and Clarke [60] six-phase model for thematic analysis was used, and the interview transcripts were cross-reviewed to spot themes until data saturation was reached and there were no new insights appearing from the data. The emerging themes were then suitably compared, coded, categorized, and embedded into sub-themes based on interrelatedness.

3.4. Ethical Considerations

Throughout the research, all ethical considerations were strictly taken into account, and study approval was obtained from the relevant institutional review board. The participants were clearly informed about the research objectives and their rights prior to the initiation of the research, and written informed consent was obtained from each trainee. Participation was made voluntary, and all respondents were given the right to withdraw at any point if they did not want to continue without any consequences. Finally, the data was handled with caution, and the responses were anonymized to maintain the confidentiality of participants throughout the research and while reporting the findings.

4. Results

At the start of the research, the overall participants (n=30) were divided into two groups, each containing 15 trainees: the experimental group (n=15) and the control group (n=15). To compare both groups' performance before and after training, pre- and post-tests were conducted. Performance was measured against both skill-based checklists (filter replacement, sensor calibration, and controlling pump pressure) and metric-based evaluations (accuracy, time, and procedural compliance), and the results are presented in Table 1. It was found that both the control and experimental groups demonstrated improvements in terms of their performance after the training intervention, as determined by the statistical significance ($p<0.05$). However, the experimental group that received VR-based training achieved a substantially higher mean gain of 19.7 points compared to the control group's gain of 9.8 points. This accounts for almost a two-fold improvement, which points to the fact that VR training is significantly more effective when it comes to skills related to replacing filters, calibrating sensors, and compliance with procedures, among other tasks.

Table 1.
Overall Performance Gain Summary – Skill-Based Checklist.

Group	Pre-Test Mean (SD)	Post-Test Mean (SD)	Mean Gain	*p*-value (Paired t-test)
Control	56.4 (±6.8)	66.2 (±7.1)	+9.8	0.021
Experimental	54.9 (±7.2)	74.6 (±6.4)	+19.7	0.000

Apart from performance gains, thorough assessments of detailed performance metrics were conducted for both groups separately. Firstly, as depicted in Table 2, the detailed performance metrics in the experimental group (VR) improved significantly and statistically after the training. Accuracy was 34% better, while procedural compliance was up by 42.3%, hence reflecting better precision and standard operating procedure compliance. Also, the time taken to accomplish a task was reduced by 28.5%, which indicates improved operational aspects. Each of the metrics was statistically significant (p<0.01), emphasizing the significant effect of VR-based training on technical performance. On the contrary, for the control group, although improvements were noted after the training in all performance metrics, the recorded changes were not significant from a statistical standpoint (p> 0.05), as noted in Table 3. The accuracy increased by 9.6% and task completion time was reduced by 7.4% while procedural compliance was improved by 12%. Thus, such small, non-significant gains imply that conventional techniques of training can be quite ineffective in enhancing technical skills compared to immersive VR-based methods.

Table 2.
Detailed Metrics – Experimental (VR) Group.

Performance Metric	Pre-Test Mean ± SD	Post-Test Mean ± SD	% Improvement	*p*-value
Accuracy (%)	62.1 ± 9.1	83.2 ± 6.4	+34.0%	0.001
Task Completion Time (min)	13.0 ± 1.7	9.3 ± 1.4	–28.5%	0.003
Procedural Compliance (%)	57.0 ± 9.8	81.1 ± 7.2	+42.3%	0.002

Table 3.
Detailed Metrics – Control Group.

Performance Metric	Pre-Test Mean ± SD	Post-Test Mean ± SD	% Improvement	*p*-value
Accuracy (%)	61.3 ± 9.8	67.2 ± 8.5	+9.6%	0.087
Task Completion Time (min)	13.5 ± 1.8	12.5 ± 1.9	–7.4%	0.164
Procedural Compliance (%)	55.8 ± 10.1	62.5 ± 8.3	+12.0%	0.079

Comparing the post-test performance between the VR and control groups showed huge differences in the VR group's advantage (Table 4). The accuracy was 23.8% higher, procedural compliance was 29.7% greater, and the task completion time was 25.6% faster in the VR group in comparison to the control group. These differences illustrated the increased effectiveness of VR-based training for enhancing the precision of the activities, following the procedures, as well as increasing the operational efficiency in the technical task.

Table 4.
Comparative Summary of Post-Test Performance.

Metric	VR Group (Post-Test)	Control Group (Post-Test)	% Difference
Accuracy (%)	83.2	67.2	+23.8%
Task Completion Time (min)	9.3	12.5	–25.6%
Procedural Compliance (%)	81.1	62.5	+29.7%

After the performance evaluation, the experimental group was asked to complete a 5-point Likert scale-based survey to assess their satisfaction and perceptions regarding the distinct aspects of the VR module, such as usability, engagement, realism, etc. The results of the survey, as presented in Table 5, showed overall higher levels of satisfaction throughout all aspects. The highest scores were obtained by the dimensions of Realism (4.7) and Engagement (4.6), signifying that the participants found the VR training immersive and engaging. Usability (4.4) and Confidence Boost (4.3) also received high ratings, reflecting that the VR system was easy to use and helped boost users' confidence. Finally, Clarity (4.2) was rated the lowest out of all dimensions, which highly suggested that some users might have encountered problems with clarity aspects, but at a minor level, given the overall high ratings. The values of standard deviations were also low, indicating consistency in participants' responses and low variance.

Table 5.
VR Group Satisfaction Survey Results.

Aspect	Mean Rating (out of 5)	Standard Deviation
Usability	4.4	0.52
Engagement	4.6	0.50
Clarity	4.2	0.65
Confidence Boost	4.3	0.58
Realism	4.7	0.49

Overall, the outcomes of the pre- and post-testing revealed a significant enhancement in the performance of the experimental group after being trained with the VR module, as opposed to the control group with the traditional mode of training. Significant enhancements were noted in skills related to replacing filters, calibrating sensors, controlling pump pressure, accuracy, task completion time, and overall procedural compliance. These findings addressed the first research question, showing the effectiveness of VR-based training for improving the precision of the activities and operational efficiency, hence in turn enhancing the technical competencies of trainees in desalination operations. In addition, the results of the satisfaction survey revealed that participants widely acknowledged the effectiveness of distinct aspects of the VR-based instructions, demonstrating high levels of satisfaction with aspects like realism, engagement, and usability, addressing the second research question.

4.1. Qualitative Results

As a final step of the current research to address the final research question, the trainees from the experimental group were asked to participate in short interviews to share their perceptions and experiences regarding the VR module, including the challenges and patterns of behavior they encountered throughout using the system. Table 6 illustrates the themes that emerged after the interviews with the experimental group's participants.

Table 6.
Themes Emerged from the Interviews.

Rank	Theme	Frequency (Percentage)	Description
1st	High Engagement with Emergency Scenarios	13 out of 15 (87%)	Emergency simulations (e.g., shutdowns) were highly realistic and beneficial.
4th	Positive Real-World Transfer	10 out of 15 (67%)	VR training made real equipment handling easier and boosted confidence.
2nd	Improvement in Procedural Recall	12 out of 15 (80%)	Participants reported better memory for SOP steps after interactive VR sessions.
5th	Overwhelm During First Session	9 out of 15 (60%)	Some trainees felt overwhelmed initially due to sensory input.
3rd	Initial Difficulty Navigating VR	11 out of 15 (73%)	Most had early trouble with headset controls and virtual movement.

As depicted in Table 6, after analyzing the data, a total of five key themes emerged, cited by a vast majority of respondents. The participants mostly gave optimistic responses when recalling their experience with VR and alluded to only two challenges that they came across when introduced to the simulated system. The first and most reported theme was high engagement with emergency scenarios, which also showed consistency with the outcomes reported in the satisfaction survey. One of the participants noted that;

> *"I was so engaged in the task that when the system displayed a shutdown, I was genuinely overwhelmed and felt panicked to react immediately since it felt almost too real and my heart was racing… Honestly, this aspect of the VR made the experience much more interesting because it showed us the possibility of emergencies rather than just simply moving on with the tasks."*

This statement signified the extent of engagement of the trainees with the VR simulation, which urged them to react immediately, making the experience immersive and more realistic while training them on how to deal with urgency dynamics and make quick decisions. Another trainee also mentioned that, "The shutdown situation was so intense and showed up unexpectedly that I forgot I was in a simulation, and the sense of urgency was further heightened by the constant timer on the screen". These findings align with the results reported by Lekea, et al. [61] who also confirmed the engaging nature of interactive scenarios and emergency situations for enhancing the effectiveness of VR-based training.

The cognitive and process improvements noted also led to another important observation that these skills were transferable to real-world operations. Many trainees insisted that using VR helped them both understand and manage the real-world resources they would use afterward. A participant expressed that;

> *"When I saw the plant machinery in real-time, it seemed very familiar because of the VR model. I understood exactly how to hold my hands, what the panel was like, and what to anticipate since everything seemed to have happened before… I believe that I can suitably implement what I have learned through it [VR module] to the actual plant more confidently."*

Likewise, another trainee noted that, "VR made the equipment seem more manageable, which otherwise would have felt frightening to manage if not for the physical elements of training".

Because their involvement was so high, participants were able to recall SOPs and other important steps much more easily. Individuals reported that their memory improved with each use of the VR modules. Participating in the simulations seemed to make memorizing sequences and tasks easier for students. One trainee asserted that “I felt like I was actually inside the plant… it [using VR] made it easier to remember the sequence of steps”. A similar sentiment was echoed by another respondent who said that;

> *“After observing SOPs through VR for the first time, I wasn’t sure what to do, yet the more times I practiced, reacting to the system in the same way, it simply got easier. It is the video that stuck with me, much more than any paper instruction manual I’ve used in the past.”*

While these results look promising, it is important to note that several participants felt overwhelmed during their first session, given that it was their first experience of VR. The vast majority of trainees said they felt bothered by too much information during their first VR session. Much of it was considered a result of the activity being so novel and requiring stimulation of many senses. Some of the statements from participants included;

> *"When I first tried the headset on, there were loads of sounds and flashes coming at me. Too much happened at once, and I didn't know the next step to take. I often didn't know what my responsibilities were, I got turned around very fast, and was super confused overall."*
>
> *"Having to look for threats, deal with motion on the runway, and respond to notifications, it was all very intense, and I felt like I needed to take a break before moving ahead. Maybe because it was my first time with VR and also my first session at training, that's why I was quite overwhelmed, but thankfully only on the first day."*

Apart from this aspect, although most participants were optimistic about the VR training, they also mentioned encountering challenges when trying out the virtual environment. Some of the participants admitted that they initially struggled to navigate the VR space and felt lost or unclear when they tried to walk around in the virtual environment or interacted with objects. For one trainee, it was a little frustrating initially, as he revealed that;

> *"I ended up turning where I shouldn't and hitting buttons I wasn't supposed to, which caused multiple errors to appear on my feedback panel. That's why I had to slowly get familiar with how motion is handled in virtual reality, and by the second session, I got used to it".*

Similar difficulties were shared by almost every participant since learning to use VR can be slightly difficult at first for anyone who does not usually use games or digital devices. Even so, participants found that once they adjusted and got oriented, they felt at ease.

5. Discussion

This study demonstrated that virtual reality training significantly enhances the technical competency of entry-level desalination plant technicians compared to traditional training methods [62]. The findings provide empirical evidence that addresses the existing research gap concerning the application of VR in desalination technician training. The discussion that follows interprets these findings in the context of the existing literature, the study's theoretical framework, and its practical implications.

5.1. Interpretation of Main Findings

The quantitative results revealed a nearly two-fold performance gain in the VR group compared to the control group. The substantial improvements in key metrics—34% in accuracy, 28.5% in task completion speed, and 42.3% in procedural compliance—underscore VR's efficacy in developing precise, efficient, and safe work practices. These results directly address the first research question, confirming that VR training effectively enhances technical competencies for desalination operations. This aligns with previous studies in other high-risk industries, such as energy and aviation, where VR has been shown to accelerate skill acquisition and improve procedural adherence [30, 32, 63]. The immersive nature of VR appears to create a learning environment where procedural memory and spatial understanding are enhanced more effectively than through passive observation or theoretical instruction [64].

5.2. Theoretical Implications

The framework of the study helps to explain the success of the VR intervention. Constructivist Learning Theory principles were evidenced when trainees actively constructed their knowledge through interacting with the virtual plant, making decisions, and seeing the results [47]. In addition, the VR module worked as a specific example of Kolb's experiential learning cycle. Trainees had Concrete Experience by completing tasks in the simulation, Reflective Observation in the feedback and debriefing, gained Abstract Conceptualized by building mental models of the designed, and changed their behavior in Active Experimentation through practicing their skills and emergencies. The technology, which embodied the simulation in a safe environment, may have impacted the level of skill retention and transfer to real life that was reported by trainees. The survey results on usability and usefulness also align with the Technology Acceptance Model (TAM), suggesting trainees viewed the VR system as an effective tool for their roles, a key concept for possible use and adoption.

5.3. Qualitative Insights and Challenges

The qualitative findings offer a deeper explanation for the quantitative outcomes. The high engagement with emergency scenarios, reported by 87% of participants, created a sense of presence and urgency that is difficult to replicate in traditional training. This immersive engagement likely drove the significant improvements in procedural compliance and task completion time under pressure. Furthermore, the theme of positive real-world transfer, cited by 67% of trainees, indicates that the skills developed in the virtual environment were perceived as directly applicable to the actual plant, validating the realism and design of the module.

However, the study also identified important challenges. The initial challenges and navigation difficulties reported by most participants align with the literature on new VR users [13, 65] indicating that the challenges posed in learning the new technology is a non-trivial factor. These issues were transient, meaning they dissipated after the first session. This suggests that with a little orientation and acclimation, these initial obstacles can be subverted so that technology can be used by someone with low digital literacy.

5.4. Limitations

The limits of this research must be considered. The sample size was small (n=30) and the training occurred over just three weeks, which may limit the generalizability of the results of this study. Furthermore, the study was focused on a specific level of technician (entry-level) and a specific suite of RO task performance which leave questions surrounding VR training of advanced skills or other desalination technologies unanswered. Finally, this study measured performance immediately post-training; the longevity of the training and performance was not assessed over time.

6. Conclusion

The current study was conducted with the primary aim of designing a virtual reality (VR) training model and evaluating its effectiveness for professional development purposes among novice technicians in desalination plants. The findings confirmed that the VR model was highly effective in enhancing technical skills, engagement, and confidence compared to traditional training approaches. Trainees in the experimental group differed from their counterparts in the control group in terms of skill acquisition and further exhibited stronger engagement, confidence, and realism in their learning experience. These results collectively affirm that VR training provides a viable and powerful platform for mastering intricate procedures through immersive, hands-on experience in a safe, simulated environment.

The implications of these findings are substantial for the water and desalination industry. This study provides a strong evidence base for policymakers, educators, and training providers to actively integrate VR modules into technician certification and orientation programs. Adopting such innovative training solutions can cultivate a more competent, confident, and safety-oriented workforce, thereby reduce operational errors and enhance plant reliability and safety. For future research, it is recommended that studies employ larger and more diverse samples, including mid- and senior-level operators, to strengthen the generalizability of the findings. Longitudinal tracking is also crucial to assess the long-term retention of VR-acquired skills and their impact on job performance. Furthermore, extending VR training system development to cover other desalination technologies and integrating artificial intelligence (AI) for personalized, adaptive feedback represents promising avenues for creating even more powerful and intelligent training ecosystems. In addition, the combination of VR, AI, and data analytics could provide a powerful model for promoting continual learning and the management of performance in technical domains.

In summary, VR-based training presents a transformative approach to technical skill development in the water sector. With continued exploration and a commitment from industry institutions to adopt these innovations, VR is poised to become a fundamental component in building a more competent, confident, and future-proofed workforce capable of addressing global water scarcity challenges.

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