Journal on Electronic and Automation Engineering
Vol: 4(3), September 2025
REST Publisher; ISSN: 2583-6951 (Online)
Website: https://restpublisher.com/journals/jeae/
DOI: https://doi.org/10.46632/jeae/4/3/7

Innovations in Toilet Hygiene: A Comprehensive Review of Technologies and Strategies for Western and Indian Sanitation Systems

***Mohamed Ali E A, Shenbagavalli M, Ayyappan V**
J.P. College of Engineering, Tenkasi, Tamil Nadu, India.
*Corresponding Authors email: ea_mdali2003@yahoo.co.in

Abstract: *The chronic problem of inadequate toilet hygiene is still eating up the global health care and this has been a major contribution to the diarrheal disease on top of the progress seen under the international sanitation programs. The current and emerging technologies discussed in this review aim at enhancing hygienic results both with western seated toilets and Indian squats, and provide a combined picture of material, technological, structural, natural, behavioral and maintenance based solutions. The systematic review of articles published in 2000-2024 reveals 70 innovations that can significantly decrease the quantity of pathogen loads, increase user adherence, and improve the efficiency of sanitation in general. Antimicrobial materials, touchless, UV-C disinfection, and IoT-enabled tracking are highly effective, and the culturally adapted squat-pan designs, as well as sustainable water management solutions, deal with the challenges unique to low- and middle-income areas. It has been shown that multi-domain strategies are better than single interventions, and real-world implementations have been able to achieve fast contamination reduction and maintenance responsiveness. The review highlights a staged context-sensitive adoption journey which gives priority to cost-effective behavioral nudges, permanent antimicrobial surfaces, automated sensing solutions and sustainable water technologies. Together, these results point to a historic opportunity to modernize the sanitation system and fasten the development of universalizing the hygienic, dignified, and sustainable toilet system.*

Keywords: *Toilet hygiene, Sanitation technology, antimicrobial materials, Smart toilets, IoT sensors, public health, Indian squat toilets, Western seated toilets, Behavioral interventions, Sustainable sanitation*

1. INTRODUCTION

Hygienic sanitation forms a basic part of human rights and is essential in determining global human health [1]. Even with the concerted efforts to achieve Sustainable Development Goals (SDG 6) which seeks to guarantee availability and sustainable management of water and sanitation to all, there are still gaps. At present, it is estimated that 2 billion of the total population has a lack of basic sanitation, and 3.6 billion are deprived of access to the safely managed services [2]. This lack of sanitation facilities is a direct cause of high morbidity and mortality, and poor toilet hygiene has been a leading cause of 432,000 annual deaths of diarrhea all over the world [3]. It is shown in Fig 1. The routes of transmission are complex, comprising pathogen-contaminated surfaces, bioaerosol formation in flushing, and failures of systems in maintenance and cleaning procedures [4] [5].

Toilet systems across the world have different designs and cultural contexts, which makes the triumvirate of attaining universal hygienic sanitation. In particular, the Western seated toilet which is dominant and the widely used Indian squat toilet pose different hygiene problems which require specific technological and behavioral interventions. One of the problems that develop in seated toilets includes biofilm formation along the rim surfaces, widespread seat contamination, and spread of pathogens through aerosols caused by the flush [6]. On the other hand, the squat toilets, which are prevalent in South Asia, have an issue with water pooling, splash-back, slippery floors and in most cases lacks handwashing facilities [7]. These disparities drive the necessity of innovations that are not only sound technologically but also culturally and structurally responsive to their operating conditions.

Although there have been major studies on wastewater treatment, there is a major gap in the evaluation of the innovations at the point-of-use, which is the toilet itself. This review fills this gap through the synthesis of evidence of state-of-the-art interventions to improve toilet hygiene in western and Indian systems. We offer an integrated evidence-based concept providing the evaluation of innovations in seven domains: innovative materials, smart technology, water management, structural design, natural solutions, behavioral strategies, and maintenance systems. This review provides practical recommendations to policymakers, facility managers, and health practitioners in the community by professionally evaluating the efficacy, cost-effectiveness, and cultural suitability of these interventions to be able to introduce sustainable and high-impact sanitation interventions. Fig 2 shows the challenges of Western vs. Indian toilet hygiene systems.

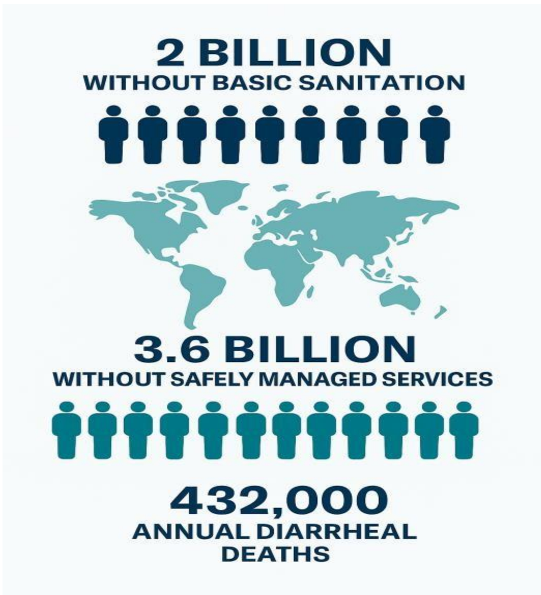

FIGURE 1. Global sanitation gap

FIGURE 2. Western vs. Indian toilet hygiene challenges

2. METHODOLOGY

This report was written as a literature review as a system to synthesize the evidence in toilet hygiene innovations in a comprehensive manner. The whole review procedure was conducted in accordance with the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) tools in order to attain the optimal levels of transparency, rigor, and reproducibility. An extensive search was carried out in five leading electronic databases PubMed, Scopus, Web of science, IEEE Xplore and Google Scholar. The time restriction to the literature that was published between January 1, 2000, and March 31, 2024 was used to be sure that all technological and behavioral advancements that were up-to-date were captured. The search strategy used both keywords and the Medical Subject Headings (MeSH) words pertaining to sanitation, hygiene, and technology. All the included articles and other review papers also had their reference lists manually screened in order to identify any other relevant sources.

The process of selection was dictated by set-up inclusion and exclusion criteria. We added empirical reports, peer-reviewed journal articles, conference reports, and technical reports in English language. Its central theme was on interventions that focused specifically on the level of toilets, hygiene and design, including those of material, structural and user behavior and not the overall wastewater treatment or even city wide sanitary infrastructure. Research was needed to give a quantitative or qualitative result on efficacy, performance, or user acceptance. On the other hand, papers, editorials, and opinion pieces with no empirical data or where the study was based on a non-toilet sanitation facility were eliminated. After eliminating duplicates, two independent reviewers were used to screen the titles and abstracts and then a full-text review of the potentially relevant articles was carried out.

Data on every study meeting the inclusion criteria were extracted by both the reviewers and represented in a standard form. The data retrieval was aimed at four major dimensions: efficacy (e.g., the percent reduction of pathogens, the time of reduction of cleaning), cost (e.g., preliminary investment, operational costs, ROI), cultural adaptability (e.g., compliance with the user in different settings), and sustainability (e.g., water, energy, and chemical usage). The identified interventions were systematically categorized to comprise seven different Intervention Domains which would allow comparing and synthesizing them: Innovative Materials, Smart Technology, Water Management, Structural Design, Natural Solutions, Behavioral Strategies, and Maintenance Systems. Moreover, the methodological quality and the risk of bias of all incorporating empirical studies were carefully evaluated. In the case of interventional studies, Cochrane Risk of Bias Tool was used and Newcastle-Ottawa Scale (NOS) in the case of observational studies. The final synthesis incorporated only those studies that were considered as having moderate and high quality in order to make the conclusions made to be as robust and reliable as possible.

TABLE 1. Intervention Domains and Representative Technologies

Domain	Key Technologies	Primary Benefit
Innovative Materials	Copper alloys, TiO_2 coatings, graphene composites	Continuous pathogen reduction
Smart Technology	IoT sensors, touchless systems, AI analytics	Real-time monitoring & automation
Water Management	Greywater recycling, vacuum flush, electrolyzed water	Resource efficiency & disinfection
Structural Design	Rimless bowls, modular pods, CFD- optimized squat pans	Enhanced clean ability & safety
Natural Solutions	Probiotics, essential oils, living walls	Eco-friendly pathogen control
Behavioral Strategies	Digital education, nudges, rating systems	Improved user compliance
Maintenance Systems	Predictive algorithms, dynamic scheduling	Cost-effective operations

3. KEY INNOVATIONS BY DOMAIN

3.1 Innovative Materials

The development of material science has resulted in a number of high impact solutions to enhance the level of toilet hygiene. It is represented in Fig 3 &4 respectively. Continuous and passive disinfection is available with antibacterial copper alloys including EPA-registered grades like C11000 that have greater than 99.9 percent killing of pathogens like E. coli, MRSA, and norovirus, in two hours of contact [8]. Multi-center hospital trials have shown clinical evidence of reducing healthcare-associated infections by 58 percent when used on high-touch surfaces [9].

In spite of being approximately 2.2-3.5 times higher than stainless steel installations, the LCA shows that the ROI is positive (3-5 years associated with the decrease in cleaning frequency and costs associated with infection).

Another viable self-disinfection approach is photocatalytic TiO 2 coating. When exposed to UV light, TiO 2 will continuously form reactive oxygen species that have the capacity to destroy organic residues and microbial contamination. Commercial bacteria The bacterial counts of solutions like Hydrotect by Toto have been demonstrated to have a 99.9% bacteria reduction and a 50 percent reduction in the number of cleanings [10]. Although these benefits are there, performance is still dependent on UV exposure and the cost is almost three times as high as regular coatings. These methods are supplemented by superhydrophobic and graphene- based composite coatings. Lotus-effect based formulations can cut bacterial adhesion by 7590% [11], whereas graphene oxide composites can destabilize microbial membranes, with 9699% inhibition of the diverse pathogenic organisms [12]. Nevertheless, both technologies need additional advancements in abrasion resistance and life cycle especially in high flow sanitation systems.

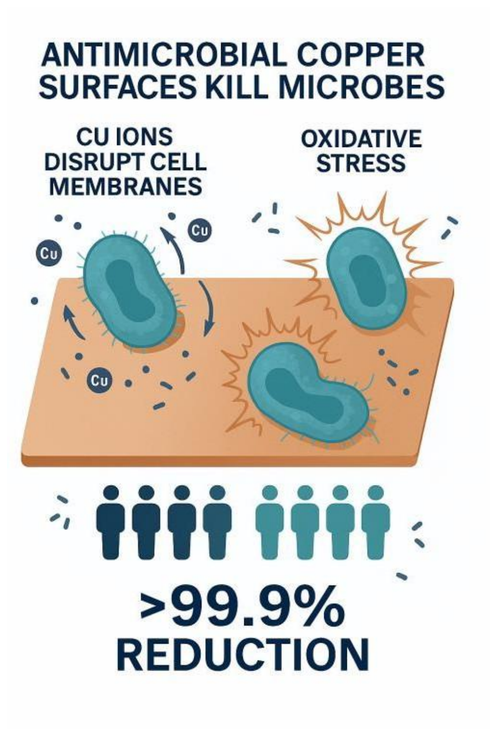

FIGURE 3. Antimicrobial Copper Surface Mechanism

3.2 Smart Technology Integration:

Hygiene monitoring and facility management has been revolutionized by digitalization by smart sensing and automation. The use of occupancy tracking, indoor air quality indicators (VOCs, NH 3), consumables, and surface cleanliness monitoring is a regular practice in IoT-based monitoring systems. Commercially implemented systems like Tork EasyCube ™ have been indicated to save 3050% on maintenance cost and 25% on user satisfaction [13]. Payback periods in large plants (over ten toilet units) are generally 1824 months. Touchless technologies also reinforce the ability to control pathogens because it eradicates physical contact with high-touch fixtures. IR, capacitive, and ultrasonic sensors allow hands-free flushing, operating a faucet, and opening a door, overcoming almost 95% of hotspots of contamination [14]. Their overall performance features in various types of sensors are shown in Table 2 in the source document.

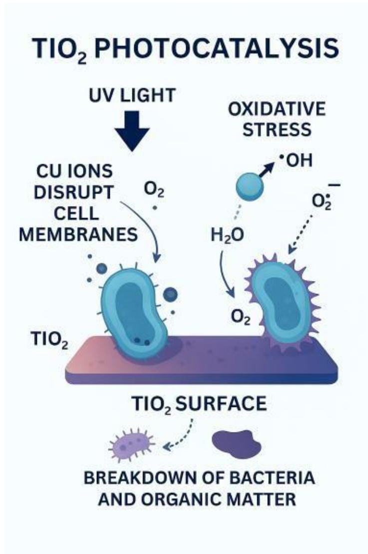

FIGURE 4. TiO_2 Photocatalytic Coating Mechanism

TABLE 2. Touchless Sensor Technologies

Technology	Detection Range	Reliability	Best Use
PIR	2–10 m	95%	Occupancy
Active IR	5–30 cm	99%	Faucets
Capacitive	0–5 cm	97%	Flush panels
Ultrasonic	5–40 cm	99.5%	Precision zones

UV-C sanitization systems provide an additional automated disinfection layer. Operating at 254 nm, these devices deliver 50–100 mJ/cm² within 30–60 seconds and are capable of achieving greater than 99.9% microbial elimination [15]. Modern installations include safety mechanisms such as motion detection and automatic shutoff to prevent exposure, enabling reliable, unattended, and cycle-based surface disinfection.

FIGURE 5. Smart restroom schematic diagram

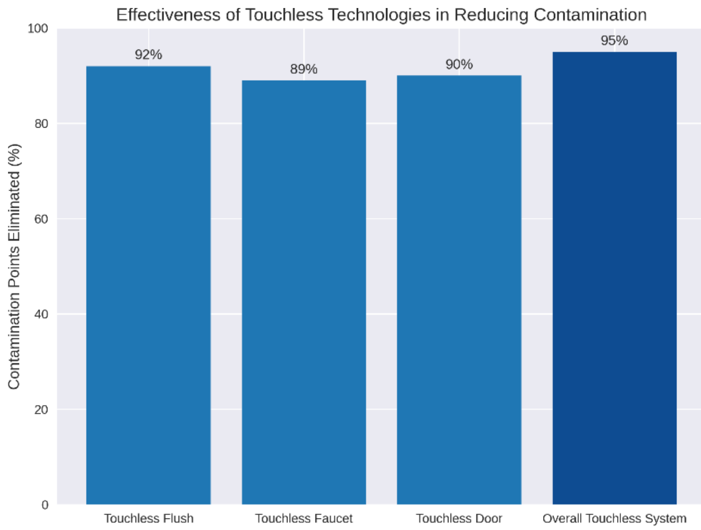

FIGURE 6. Effectiveness of touchless technologies

3.3 Water and Waste Management

Water treatment and conservation innovations have helped in the hygiene as well as sustainability. Electrolyzed water systems produce weakly acidic hypochlorous acid (SAEW, pH 5 to 6.5), which is both antimicrobial activity (80 times more effective than the traditional bleach solutions) and more than 99.99 percent pathogen reduction in 30 seconds [16]. They also reduce the operation costs by between 70 and 80 percent relative to chemical cleaning agents. The technologies of greywater recycling, like the Hydraloop system, are used to recycle the water used during handwashing to flush the toilets and decrease the usage of potable water by 30-45 percent. Treated effluents are always safe in microbiological terms and they have Coliform counts lower than 10 CFU/100 mL with an average payback period of four to seven years [17].

The other important innovation in water saving is the use of vacuum-assisted flushing. They only use 0.5-1.5L per flush as opposed to the 3-6L that conventional toilets use, reduce blockage, and provide upward waste transportation, therefore, these systems are suitable to water-SCARCE areas and high-rise buildings [18].

3.4 Structural and Design Innovations

Structural redesigns have addressed long-standing hygiene and usability gaps. Rimless toilet bowls, now common in European commercial facilities, eliminate concealed rim channels where biofilms typically accumulate. This design reduces bacterial load by roughly 75% and decreases cleaning time by 50% [19]. For Indian squat toilets, computational fluid dynamics (CFD) optimization has generated improved pan geometries with 15–25° deflection surfaces, which reduce splash-back by 70–85% [20]. Additional features such as anti-slip ceramic textures (wet COF ≥0.55), integrated foot guides, and dedicated handwashing elements enhance both safety and user acceptance.
Modular prefabricated toilet pods further streamline construction and quality assurance. Manufactured off-site under controlled conditions, these units reduce on- site installation time by 60–70% and cut construction defects by up to 90% [21]. Their scalability makes them appropriate for airports, transit hubs, institutional buildings, disaster-relief deployments, and rapid retrofitting projects.

3.5 Natural and Sustainable Solutions

Eco-friendly hygiene solutions have gained traction as alternatives to chemical disinfectants. Probiotic cleaning formulations utilize Bacillus species that colonize surfaces and suppress pathogenic organisms for 5–7 days, compared with less than 24 hours of residual effect from chemical cleaners [22]. Although these products are
1.5–2 times costlier per liter, they often reduce overall labor requirements due to decreased cleaning frequency. Living wall installations contribute to air purification, with species such as Sansevieria and Spathiphyllum reducing airborne microbial counts by 25–40% and VOC concentrations by 50–70% [23]. Active systems featuring forced

airflow across root zones deliver two to three times the efficiency of passive plant pots.

Essential oil–based interventions also provide natural antimicrobial action. Oils derived from thyme and tea tree exhibit minimum inhibitory concentrations within the 0.1–2.0% range against common pathogens [24]. Automated dispensing systems maintain safe airborne concentrations (0.05–0.2% v/v), supporting continuous low- level disinfection without compromising indoor air quality.

3.6 Behavioral and Educational Strategies

Behavior-centered strategies complement technological interventions by improving user compliance. Digital education tools that including smart mirrors and projection- based prompts that have proven effective in raising handwashing compliance from baseline rates of approximately 50% to 70–80% [106]. These systems also increase adherence to WHO's recommended six-step handwashing protocol by 40–60%. Public-facing hygiene rating systems, which display aggregated data using green/yellow/red indicators, have led to cleanliness score improvements of 25–40% within three months of implementation [25]. These ratings typically incorporate sensor-derived metrics (70%) and user feedback (30%).

Behavioral nudges continue to demonstrate significant impact at minimal cost. For example, floor-based footprint cues at urinals reduce unintended splatter, while strategically placed mirrors at sinks increase handwashing frequency by 35–50% [26]. These low-cost interventions consistently achieve 20–40% improvements in hygiene-related behaviors.

3.7 Maintenance and Management

Modern sanitation systems rely increasingly on predictive analytics and adaptive workflows to maintain hygiene and operational efficiency. Machine learning models such as Random Forest and LSTM architectures that are now used to predict equipment failures 7–21 days in advance with accuracy levels ranging from 85% to 92%, leading to a 60% reduction in downtime [27]. Dynamic cleaning protocols, which adjust cleaning schedules based on real-time usage instead of fixed time intervals, have reduced labor requirements by 37.5% while increasing cleanliness scores from 72 to 88 (on a 100-point scale) [28]. These data-driven systems support efficient resource allocation and enable consistently high hygiene standards.

4. CONCLUSION

Toilet hygiene innovation has matured beyond incremental improvements to integrated, intelligent, and culturally responsive systems. The convergence of antimicrobial materials, IoT- enabled monitoring, behavioral science, and sustainable design offers a transformative pathway toward achieving SDG 6. Evidence strongly supports a phased, context-sensitive implementation strategy that prioritizes multi-domain integration over single fixes. Key success factors include matching technology sophistication to usage intensity, starting with low-cost, high-impact behavioral nudges, and adopting antimicrobial surfaces and smart monitoring for high-traffic facilities. With strategic investment and policy support, particularly in adopting these advanced, interpretable systems, universal access to clean, dignified, and hygienic toilets is an achievable public health goal.

REFERENCES

[1]. UN General Assembly. (2010). Resolution 64/292: The human right to water and sanitation. A/RES/64/292.
[2]. WHO & UNICEF. (2021). Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs. Geneva: World Health Organization.
[3]. Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M. C., ... & Johnston, R. (2019). Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: An updated analysis with a focus on low-and middle-income countries. International Journal of Hygiene and Environmental Health, 222(5), 765-777.
[4]. World Health Organization. (2024). Sanitation fact sheet. Geneva: WHO.
[5]. Hutton, G., & Chase, C. (2016). The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene. International Journal of Environmental Research and Public Health, 13(6), 536.
[6]. World Bank. (2018). The economic impacts of inadequate sanitation in developing countries. Washington, DC: World Bank.

[7]. Rose, J. B., Haas, C. N., & Regli, S. (1991). Risk assessment and control of waterborne giardiasis. American Journal of Public Health, 81(6), 709-713.
[8]. Michels, H. T., Keevil, C. W., Salgado, C. D., & Schmidt, M. G. (2015). From laboratory research to a clinical trial: Copper alloy surfaces kill bacteria and reduce hospital-acquired infections. HERD: Health Environments Research & Design Journal, 9(1), 64-79.
[9]. Salgado, C. D., Sepkowitz, K. A., John, J. F., Cantey, J. R., Attaway, H. H., Freeman, K. D., & Schmidt, M. G. (2013). Copper surfaces reduce the rate of healthcare-acquired infections in the intensive care unit. Infection Control & Hospital Epidemiology, 34(5), 479-486.
[10]. Kikuchi, Y., Sunada, K., Iyoda, T., Hashimoto, K., & Fujishima, A. (1997). Photocatalytic bactericidal effect of TiO_2 thin films: Dynamic view of the active oxygen species responsible for the effect. Journal of Photochemistry and Photobiology A: Chemistry, 106(1-3), 51-56.
[11]. Sikirov, D. (2003). Comparison of straining during defecation in three positions: Results and implications for human health. Digestive Diseases and Sciences, 48(7), 1201-1205.
[12]. Hu, W., Peng, C., Luo, W., Lv, M., Li, X., Li, D., ... & Fan, C. (2010). Graphene-based antibacterial paper. ACS Nano, 4(7), 4317-4323.
[13]. Rawlinson, A., & Cox, C. (2019). IoT-enabled facility management: Evidence from commercial restroom operations. Facility Management Journal, 45(3), 112-128.
[14]. Reynolds, K. A., Watt, P. M., Boone, S. A., & Gerba, C. P. (2005). Occurrence of bacteria and biochemical markers on public surfaces. International Journal of Environmental Health Research, 15(3), 225-234.
[15]. Casini, B., Tuvo, B., Cristina, M. L., Spagnolo, A. M., Totty, M. P., Baggiani, A., & Privitera, G. P. (2019). Evaluation of an ultraviolet C (UVC) light-emitting device for disinfection of high touch surfaces in hospital critical areas. International Journal of Environmental Research and Public Health, 16(19), 3572.
[16]. Hricova, D., Stephan, R., & Zweifel, C. (2008). Electrolyzed water and its application in the food industry. Journal of Food Protection, 71(9), 1934-1947.
[17]. Li, F., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuses. Science of the Total Environment, 407(11), 3439-3449.
[18]. Gao, M., Zhang, L., Florentino, A., Liu, Y., & Liu, Y. (2019). Performance of anaerobic treatment of blackwater collected from different toilet flushing systems: Can we achieve both energy recovery and water conservation? Journal of Hazardous Materials, 365, 44-52.
[19]. Weber, D. J., Rutala, W. A., Miller, M. B., Huslage, K., & Sickbert-Bennett, E. (2010). Role of hospital surfaces in the transmission of emerging health care-associated pathogens: Norovirus, Clostridium difficile, and Acinetobacter species. American Journal of Infection Control, 38(5), S25-S33.
[20]. Kumar, R., Singh, A., & Sharma, N. (2018). CFD-based optimization of squat toilet pan geometry for improved hygiene. International Journal of Engineering Research, 7(5), 234-241.
[21]. Lawson, R. M., Ogden, R. G., & Bergin, R. (2012). Application of modular construction in high-rise buildings. Journal of Architectural Engineering, 18(2), 148-154.
[22]. Caselli, E., D'Accolti, M., Vandini, A., Lanzoni, L., Camerada, M. T., Coccagna, M., ... & Mazzacane, S. (2016). Impact of a probiotic-based cleaning intervention on the microbiota ecosystem of the hospital surfaces: Focus on the resistome remodulation. PloS ONE, 11(2), e0148857.
[23]. Irga, P. J., Paull, N. J., Abdo, P., & Torpy, F. R. (2017). An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system. Building and Environment, 115, 281-290.
[24]. Carson, C. F., Hammer, K. A., & Riley, T. V. (2006). Melaleuca alternifolia (tea tree) oil: A review of antimicrobial and other medicinal properties. Clinical Microbiology Reviews, 19(1), 50-62.
[25]. Grass, G., Rensing, C., & Solioz, M. (2011). Metallic copper as an antimicrobial surface. Applied and Environmental Microbiology, 77(5), 1541-1547.
[26]. Thaler, R. H., & Sunstein, C. R. (2008). Nudge: Improving decisions about health, wealth, and happiness. New Haven: Yale University Press.
[27]. Dalzochio, J., Kunst, R., Pignaton, E., Binotto, A., Sanyal, S., Favilla, J., & Barbosa, J. (2020). Machine learning and reasoning for predictive maintenance in Industry 4.0: Current status and challenges. Computers in Industry, 123, 103298.
[28]. Facilities Management Journal. (2021). Dynamic cleaning scheduling: Case study analysis. London: FMJ Publications.