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Advancements in Dry Toilet Technologies: A Comprehensive Review of Design, Materials and Waste Treatment Approaches

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Abstract: **This literature review examines recent advancements in dry toilet technologies, with particular emphasis on degradable materials for toilet bowls and innovative waste treatment processes. The review encompasses seven key areas: current dry toilet designs, degradable materials for toilet bowl films, human waste treatment processes in waterless systems, pathogen elimination and safety considerations, nutrient recovery from treated waste, environmental impact assessment, and social acceptance challenges. Recent trends reveal a significant shift toward waterless systems incorporating urine diversion technology, biodegradable materials, and circular economy approaches to waste management. Notable innovations include sealing mechanisms that enhance user experience while maintaining environmental benefits, combustion-based treatment systems that effectively eliminate pathogens, and biodegradable films made from cellulose fibers with improved disintegration properties. This review synthesizes findings from peer-reviewed research published between 2022 and 2025, alongside industry developments. The findings indicate that while significant technological progress has been made, challenges remain in balancing material durability, degradability, cost-effectiveness, and user acceptance. This review contributes to the growing body of knowledge on sustainable sanitation solutions that conserve water resources while effectively managing human waste.**

Keywords:

I. INTRODUCTION

Sanitation remains a critical global challenge, with approximately 3.5 billion people - nearly half of the world's population - lacking access to safe sanitation facilities [1]. Conventional water-based sanitation systems, while effective in many contexts, present significant limitations including high water consumption, dependence on extensive infrastructure, and vulnerability to climate change impacts such as droughts and floods. These challenges have spurred interest in alternative approaches, particularly dry toilet technologies that operate with minimal or no water use.

Dry toilets represent a diverse category of sanitation solutions designed to manage human waste without relying on water for flushing. These systems range from simple pit latrines to sophisticated composting toilets and technologically advanced urine-diverting systems. The fundamental principle uniting these approaches is the separation of human waste from water cycles, thereby conserving water resources while creating opportunities for waste treatment, pathogen elimination, and potential resource recovery [2].

The development of effective dry toilet technologies intersects multiple disciplines, including materials science, microbiology, environmental engineering, and social sciences. Of particular interest is the potential for innovative materials - specifically degradable films for toilet bowls - to enhance user experience while maintaining environmental benefits. Such materials must balance seemingly contradictory requirements: sufficient durability during use, yet rapid degradability after disposal.

A. Objectives of the Review

This literature review aims to synthesize current knowledge and recent innovations in dry toilet technologies, with particular emphasis on degradable materials for toilet bowls and associated waste treatment processes. The specific objectives are to:

1. Identify and evaluate recent innovations in dry toilet designs and technologies;
2. Assess the performance characteristics of degradable materials suitable for toilet bowl films;
3. Analyze human waste treatment processes applicable to waterless systems;
4. Examine approaches to pathogen elimination and safety assurance;
5. Evaluate methods for nutrient recovery from treated human waste;
6. Assess the environmental impacts and sustainability of dry toilet technologies;
7. Identify social acceptance factors and implementation challenges.

B. Scope of the Review

This review encompasses literature published between 2022 and 2025, focusing on peer- reviewed academic research, technical reports from reputable organizations, and documented industry innovations. The geographical scope is global, though particular attention is given to technologies applicable in both developed and developing contexts.

While the review acknowledges the historical development of dry toilet technologies, it emphasizes recent advancements that could inform the development of a new type of dry toilet incorporating a special degradable film for the toilet bowl. The review excludes detailed examination of conventional water-based sanitation systems except where direct comparisons with dry technologies are instructive.

Similarly, it does not extensively cover policy frameworks or economic analyses beyond their relevance to implementation challenges.

C. Research Questions

The review addresses the following key research questions:

1. What are the most recent innovations in dry toilet designs, and how do they address limitations of earlier approaches?

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2. What degradable materials have been developed or adapted for toilet bowl films, and what are their performance characteristics?
3. How can human waste be effectively treated in waterless systems to ensure safety and resource recovery?
4. What approaches to pathogen elimination have proven most effective in dry toilet systems?
5. What methods exist for recovering nutrients from treated human waste, and what are their relative efficiencies?
6. How do dry toilet technologies compare to conventional systems in terms of environmental impact?
7. What social, cultural, and practical factors influence the acceptance and implementation of dry toilet technologies?

D. Structure of the Review

This review is organized thematically, with each section addressing one of the key aspects of dry toilet technologies. Following this introduction and methodology section, the main body examines current dry toilet designs, degradable materials, waste treatment processes, pathogen elimination, nutrient recovery, environmental impacts, and social acceptance factors. The discussion section synthesizes findings across these themes, identifies research gaps, and considers implications for future development. The conclusion summarizes the key insights.

II. METHODOLOGY

A. Search Strategy

A comprehensive search strategy was employed to identify relevant literature on dry toilet technologies published between January 2022 and May 2025. The search was conducted in multiple stages, beginning with broad queries and progressively refining based on initial results.

1) Databases and Sources

The following electronic databases and sources were searched:
Academic databases: PubMed Central, ScienceDirect, Web of Science, MDPI, ACS Publications;
Technical repositories: Engineering Village, IEEE Xplore;
Organizational publications: Gates Foundation, World Health Organization, Sustainable Sanitation Alliance;
Industry sources: Patents, product documentation, technical specifications.

2) Search Terms

Search terms were organized into three categories and combined using Boolean operators:
Category 1: Toilet Technologies - "dry toilet" OR "waterless toilet" OR "composting toilet" OR "urine-diverting toilet" OR "ecological sanitation" OR "eco-san" OR "compost latrine";
Category 2: Materials and Design - "degradable film" OR "biodegradable material" OR "cellulose fiber" OR "toilet bowl design" OR "disintegration efficiency" OR "water-soluble film" OR "antimicrobial coating";
Category 3: Waste Treatment and Recovery - "human waste treatment" OR "pathogen elimination" OR "nutrient recovery" OR "composting process" OR "microbiome" OR "waste valorization" OR "circular economy".

B. Selection Criteria

1) Inclusion Criteria

- Publications dated between January 2022 and May 2025;
- Peer-reviewed journal articles, conference proceedings, technical reports, and patents;
- Studies focusing on dry toilet technologies, degradable materials, or relevant waste treatment processes;
- Publications in English;
- Studies providing empirical data, theoretical frameworks, or comprehensive reviews.

2) Exclusion Criteria

- Publications older than January 2022, except for seminal works providing essential context;
- Non-English publications;
- Non-peer-reviewed blogs, opinion pieces, or commercial advertisements;
- Studies focusing exclusively on conventional water-based sanitation without relevance to dry systems.

C. Study Selection Process

The selection process followed a systematic approach:

1. Initial screening of titles and abstracts against inclusion/exclusion criteria;
2. Full-text review of potentially relevant publications;
3. Quality assessment based on methodological rigor,
4. Final selection of studies for inclusion in the review.

D. Data Extraction and Synthesis

From each selected publication, the following information was extracted: study design and methodology, key findings and conclusions, technological innovations or material properties, performance metrics and evaluation criteria, limitations and research gaps identified.

Data synthesis followed a thematic approach, organizing findings according to the seven key areas identified in the research questions. Within each thematic area, studies were compared and contrasted to identify patterns, contradictions, and emerging trends.

E. Quality Assessment

The quality of included studies was assessed based on: methodological rigor and appropriateness, sample size and representativeness (for empirical studies), validity of measurements and analyses, transparency in reporting results, acknowledgment of limitations, and relevance to research questions. This assessment informed the weight given to different studies in the synthesis and discussion of findings.

III. THEMATIC REVIEW OF DRY TOILET TECHNOLOGIES

A. Current Dry Toilet Designs and Technologies

The landscape of dry toilet technologies has evolved significantly in recent years, with innovations addressing previous limitations in user experience, waste management efficiency, and environmental impact. This section examines the major

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1) Urine-Diverting Dry Toilets (UDDTs)

Urine-diverting dry toilets represent one of the most significant advancements in waterless sanitation technology. These systems separate urine from solid waste at the source, offering several advantages over traditional composting toilets including odor reduction, improved waste treatment efficiency, and enhanced resource recovery potential [2] and [3]. A comprehensive review by reference [3] highlighted that UDDTs significantly reduce the volume of waste requiring treatment while facilitating more efficient nutrient recovery compared to mixed-waste systems.

A notable recent innovation in this category is the CompoCloset S1 Sealing Toilet, launched in April 2025. This system incorporates urine diversion technology that separates liquids from solids, reducing plastic bag use by up to 80% compared to conventional dry flush toilets. The S1 features a powerful sealing mechanism that locks away solid waste after each use, addressing odor concerns that have historically limited user acceptance of dry toilets. With a battery capacity supporting up to 50 flushes per charge and requiring no chemicals or water, this system exemplifies the trend toward more user-friendly and environmentally sustainable dry toilet designs [4].

Reference [5] reported similar advancements with their Optima 7 vacuum toilet, which achieves 90% water savings compared to traditional gravity toilets while maintaining high user satisfaction. This hybrid approach - using minimal water with vacuum technology - represents an intermediate solution between conventional flush toilets and completely waterless systems, potentially offering a transition pathway for contexts where complete water elimination faces resistance.

2) Packaging and Sealing Systems

Recent innovations in packaging and sealing technologies have significantly improved the user experience of dry toilets, particularly for mobile and temporary applications.

The Modiwell Dry Flush Toilet, introduced in 2025, exemplifies this approach with its lightweight design (17 pounds), compact dimensions (17" × 17" × 11"), and foldable structure for easy storage. The system employs "automatic hot garbage disposal technology" in conjunction with biodegradable garbage bags that comply with European Union EN 13432 industrial compostability standards. With a built-in 5200mAh rechargeable battery supporting 70-100 uses on a single charge, this system addresses key usability concerns while maintaining environmental benefits [6].

Comparative analysis of the Modiwell system with the earlier Laveo dry flush toilet reveals significant improvements in weight reduction (37% lighter), increased usage capacity per refill (30 uses versus 15-25), and enhanced environmental credentials through fully biodegradable waste bags rather than cartridges [6]. These advancements demonstrate the industry's response to user demands for more portable, convenient, and environmentally responsible dry toilet solutions.

3) Combustion-Based Systems

The Gates Foundation has pioneered the development of combustion-based dry toilet systems as part of its Reinvented Toilet initiative. These systems use combustion for solids processing and recycle wastewater for flushing and non-potable reuse. The technology offers several advantages over traditional approaches: it kills pathogens more reliably than standard systems, significantly reduces the volume of residual material, and produces biochar or ash that can be safely disposed of in gardens or trash. Importantly, the technology can be scaled from single-household units to systems serving entire buildings [1].

Three primary configurations have emerged from this initiative: 1. Single household toilets with attached treatment systems 2. Systems that pipe toilets, sinks, and showers to external treatment units replacing septic tanks 3. Centralized systems for apartment buildings with treatment units in basements or other accessible locations.

These combustion-based systems represent a significant departure from traditional composting approaches, offering potentially faster and more complete pathogen elimination while reducing the volume of waste requiring disposal [1].

Reference [8] conducted a comparative life cycle analysis of Sol-Char sanitation systems (using solar energy for thermal treatment) against anaerobic digestion approaches, finding that while Sol-Char systems had higher energy requirements, they achieved superior pathogen elimination and produced biochar with valuable soil amendment properties.

Reference [9] explored energy-autonomous technologies for public toilets, demonstrating that integrated renewable energy systems could support combustion-based treatment while minimizing external energy requirements. Their prototype achieved energy self-sufficiency through a combination of solar photovoltaics, small-scale wind turbines, and energy recovery from waste treatment processes, suggesting a pathway toward more sustainable implementation of these advanced systems.

4) Resource-Oriented Sanitation Systems

Reference [10] developed an LCA approach for vacuum-based sanitation systems, offering valuable insights into environmental performance.

This integrated approach to resource-oriented sanitation represents an emerging trend in dry toilet technologies, moving beyond waste disposal to view human excreta as a valuable resource within broader material cycles. As reference [3] noted, "the paradigm shift from waste disposal to resource recovery requires rethinking not only toilet design but the entire sanitation value chain, from collection through treatment to end-use applications”.

5) Comparative Analysis of Current Technologies

Table 1 presents an expanded comparative analysis of key features across the major dry toilet technologies discussed above. This expanded comparison highlights the diversity of approaches in current dry toilet technologies, with each system offering distinct advantages for different use contexts.

The evolution from simple composting toilets to sophisticated resource-oriented systems demonstrates the

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field's maturation and increasing alignment with circular economy principles and user expectations for convenience and aesthetics.

B. Degradable Materials for Toilet Bowl Films

The development of effective degradable materials for toilet bowl films represents a critical frontier in dry toilet technology. These materials must balance contradictory requirements: sufficient durability and water resistance during use, yet rapid degradability after disposal. Recent research has focused on cellulose-based materials, biodegradable polymers, and antimicrobial coatings to address these challenges.

1) Cellulose-Based Materials

Cellulose fibers have emerged as a promising base material for degradable toilet bowl films due to their inherent biodegradability, renewable sourcing, and adaptable properties. Reference [11] conducted a comprehensive study on improving the disintegration efficiency and antibacterial properties of disposable toilet seat cover sheets made from cellulose fibers. Their research investigated the disintegration characteristics of flushable cover sheets prepared under different refining conditions, finding that pulp stock with a freeness of approximately 650 mL CSF (Canadian Standard Freeness) provided optimal balance between structural integrity during use and disintegration properties similar to toilet tissue paper.

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Table 1. Key features across the major dry toilet technologies.

Feature	**Urine- Diverting Systems (CompoCloset S1, Evac Optima 7)**	**Packaging Systems (Modiwell)**	**Combustion- Based Systems (Gates Foundation, Sol-Char)**	**Resource- Oriented Systems (Vacuum Collection)**
Water Usage	None to minimal	None	Minimal (for recycling)	Minimal (vacuum transport)
Energy Requirements	Battery- powered (50-100 flushes/ charge)	Battery- powered (70-100 uses/ charge)	Moderate to high (can be renewable)	Moderate (vacuum pumps)
Waste Treatment	Separation and sealing	Sealing in biodegradable bags	Thermal treatment and water recycling	Integrated treatment with kitchen waste
Pathogen Management	Physical containment	Physical containment	Thermal destruction	Biological treatment
Portability	Moderate (compact design)	High (lightweight, foldable)	Low (fixed installation)	Very low (infrastructure-dependent)
Maintenance	Bag replacement, cleaning	Biodegradable bag replacement	System servicing, ash removal	System servicing, pipe maintenance
Environmental Impact	Reduced plastic waste, water conservation	Biodegradable materials, zero water use	Produces biochar/ash, energy consumption	Circular economy approach, resource recovery
Target Applications	Recreational vehicles, boats, off-grid homes	Mobile applications, emergency use	Permanent installations, multi-unit buildings	Urban developments, eco- communities
Cost Range	Moderate	Low to moderate	High	High (infrastructure)
Nutrient Recovery Potential	High (separate streams)	Low (mixed waste)	Moderate (in biochar)	Very high (integrated system)

To enhance water resistance while maintaining degradability, reference [11] incorporated alkyl ketene dimer (AKD) at a 0.2% concentration. This addition provided sufficient temporary water resistance without significantly impeding subsequent degradation. The researchers also added a 1% organic antibacterial agent to impart antimicrobial properties, addressing hygiene concerns associated with toilet surfaces.

Reference [12] provided a comprehensive review of biodegradability characteristics across various cellulose-based materials, noting that cellulosic materials demonstrate superior biodegradability compared to synthetic or bio-based plastics, though they degrade more slowly than starch-based alternatives. Their analysis of degradation mechanisms in different environments (soil, compost, aquatic) offers valuable insights for optimizing cellulose-based films for toilet applications, particularly regarding the balance between temporary water resistance and ultimate biodegradability.

The authors emphasized that "cellulose biodegradability, while generally rapid and natural, has a rate and extent that depends on a complex and sometimes subtle interplay of

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factors including crystallinity, surface area, lignin content, and environmental conditions” [12]. This nuanced understanding is essential for designing cellulose-based films with controlled degradation timelines suitable for dry toilet applications.
Reference [13] explored novel bio-based papers derived from seaweed and coconut fiber, demonstrating that these abundant, renewable materials could produce films with excellent water resistance and controlled biodegradability. Their research highlighted the potential for locally sourced, region-specific materials to address both performance requirements and sustainability concerns in degradable film development.

2) Biodegradable Polymers and Composites

Beyond pure cellulose materials, recent research has explored biodegradable polymers and cellulose-polymer composites for toilet applications. The Modiwell dry flush toilet system utilizes garbage bags made from biodegradable materials compliant with European Union EN 13432 industrial compostability standards [6]. While specific polymer compositions are proprietary, these materials represent significant advancements in balancing functionality with environmental credentials.
Reference [14] developed mechanically tunable, compostable, healable, and scalable engineered living materials (MECHS) with potential applications in degradable films. These innovative materials "biodegrade completely in 15-75 days, while their mechanical properties are comparable to petrochemical plastics” [14]. Such materials offer a promising direction for toilet bowl films that require both durability during use and rapid degradation after disposal.
Reference [15] investigated plant-based chitosan for biodegradable packaging films, demonstrating that these materials could achieve water resistance comparable to conventional plastics while maintaining complete biodegradability. Their research highlighted the potential for adapting food packaging innovations to toilet applications, particularly regarding barrier properties and controlled degradation.
Laveo's cartridge technology, made from sugarcane bagasse, exemplifies another approach to biodegradable materials for toilet applications. These cartridges incorporate urine powder to increase usage capacity, demonstrating how material innovations can enhance functional performance while maintaining biodegradability [6].

3) Antimicrobial Properties and Safety Considerations

The integration of antimicrobial properties into degradable toilet materials has gained increased attention, particularly following heightened hygiene awareness during the COVID-19 pandemic. Reference [11] demonstrated that incorporating a 1% organic antibacterial agent into cellulose-based toilet seat covers provided effective antimicrobial protection without compromising degradability.
Reference [16] highlighted concerns regarding antimicrobial pollution from sanitation systems, noting that traditional approaches often release antimicrobial compounds into the environment. Their research advocates for materials and designs that provide necessary hygiene protection while minimizing environmental contamination, suggesting that biodegradable carriers for antimicrobial agents may offer a more sustainable approach.
Reference [17] investigated polymicrobial outbreaks in healthcare settings, emphasizing the importance of water-safe concepts in infection control. Their research has implications for dry toilet technologies, particularly regarding the integration of antimicrobial properties that target specific pathogens without contributing to antimicrobial resistance or environmental contamination.

4) Testing Methodologies and Standards

Standardized testing methodologies for degradable toilet materials remain an evolving area. Reference [11] referenced ISO 12625-17 for evaluating the disintegration characteristics of flushable materials, demonstrating the importance of established protocols in assessing material performance. However, the researchers also noted limitations in current standards, particularly regarding the balance between water resistance during use and subsequent degradability.
The European Union EN 13432 industrial compostability standard has emerged as a reference point for biodegradable materials in toilet applications, as evidenced by Modiwell's compliance claims [6]. However, regional variations in standards and regulations present challenges for global product development, with California's specific regulations for "compostable" products based on ASTM standards rather than EN 13432 highlighting the complexity of the regulatory landscape [18].

5) Future Directions in Material Development

Emerging research suggests several promising directions for degradable toilet bowl films. Reference [12] identified potential in tailored cellulose composites with controlled degradation timelines, while reference [11] highlighted opportunities for optimizing refining conditions to achieve specific performance characteristics. The integration of nanotechnology with biodegradable materials represents another frontier, potentially offering enhanced properties without compromising environmental credentials.
Reference [14] demonstrated the potential for engineered living materials incorporating beneficial microorganisms that could actively contribute to waste decomposition while providing structural properties. This innovative approach could create synergies between the toilet bowl film and subsequent waste treatment processes, potentially accelerating decomposition and enhancing resource recovery.
The ideal degradable film for toilet bowl applications would combine sufficient water resistance during the usage period (3-5 months), mechanical strength to withstand normal use conditions, antimicrobial properties for hygiene assurance, rapid and complete degradation after disposal, cost-effective manufacturing processes , and renewable and sustainable raw materials.
Current research suggests that while significant progress has been made, achieving this ideal combination remains a

challenge requiring continued innovation in materials science and processing technologies.

C. Human Waste Treatment Processes in Waterless Systems

The effective treatment of human waste in waterless systems represents a critical component of dry toilet technologies. Recent research has advanced our understanding of treatment processes, with particular emphasis on composting mechanisms, dehydration techniques, combustion approaches, and chemical treatments.

1) Composting Processes and Microbiome Science

Reference [2] explored compost microbiome dynamics and their implications for sanitation.

The authors noted that effective composting of human excrement typically involves a succession of microbial communities, beginning with rapid-growing bacteria that break down readily available organic compounds, followed by fungi and actinomycetes that degrade more recalcitrant materials such as cellulose and lignin. This succession corresponds to temperature phases within the composting process: mesophilic (20-45°C), thermophilic (45-70°C), and maturation (cooling to ambient temperature).

The thermophilic phase is particularly crucial for pathogen inactivation, with temperatures above 55°C for at least three consecutive days generally considered sufficient to eliminate most human pathogens [2]. In a related editorial, reference [19] emphasized the need for a new, long-term strategy for managing human excrement to facilitate health equity and promote environmental sustainability. They argued that "microbiome multi-omics can accelerate human excrement composting science" by providing deeper insights into microbial dynamics and functional capabilities. Their work highlighted how advanced sequencing technologies can identify not only which microorganisms are present but also their metabolic activities and interactions, potentially enabling more efficient and reliable composting processes.

Reference [3] provided a comprehensive review of dry toilet management approaches, with particular emphasis on brown water (feces) composition, treatment, and potential uses. Their analysis of composting systems across different geographical and climatic contexts revealed significant variations in performance, highlighting the importance of context-specific design and management practices. The authors noted that "composting efficiency depends on multiple factors including temperature, moisture content, carbon-to-nitrogen ratio, and microbial inoculation", emphasizing the need for adaptive management approaches rather than standardized solutions.

2) Dehydration and Desiccation Techniques

Dehydration represents another approach to human waste treatment in dry toilet systems, particularly in arid regions or where rapid volume reduction is prioritized over nutrient recovery. Unlike composting, which relies on microbial activity to transform waste, dehydration aims to remove moisture and thereby inhibit biological activity, including pathogen survival and reproduction.

Modern dehydration systems often incorporate forced ventilation, solar heating, or other mechanisms to accelerate moisture removal. These systems typically separate urine from solid waste to facilitate more efficient drying of fecal matter. While simple in principle, effective dehydration requires careful attention to ventilation design, temperature management, and humidity control to prevent odor issues and ensure sufficient pathogen reduction [16].

Reference [20] investigated pathogen transmission through water, feces, and contaminated surfaces, noting that moisture content is a critical factor in pathogen survival and transport. Her research demonstrated that reducing moisture content below 25% significantly inhibited the survival of many enteric pathogens, though some resistant forms (particularly helminth eggs and certain bacterial spores) could persist even in desiccated environments. These findings have important implications for dehydration-based treatment systems, suggesting that while moisture reduction is valuable, it may need to be combined with other approaches for comprehensive pathogen management.

A limitation of dehydration approaches is their reduced capacity for breaking down complex organic compounds compared to composting systems. Consequently, dehydrated waste may require additional treatment before safe reuse, particularly for agricultural applications. However, for contexts where final disposal rather than reuse is the primary goal, dehydration offers advantages in terms of simplicity, odor control, and volume reduction.

3) Combustion and Thermal Treatment

The reference [1] invested in scaling up affordable reinvented toilet solutions for underserved populations.

Reference [8] conducted a comparative life cycle analysis of Sol-Char sanitation systems against anaerobic digestion approaches. Their research demonstrated that while Sol-Char systems had higher energy requirements, they achieved superior pathogen elimination (>99.9999% reduction) and produced biochar with valuable soil amendment properties. The authors noted that "the energy intensity of thermal treatment must be balanced against its superior performance in pathogen elimination and volume reduction", suggesting that context-specific factors should determine the optimal approach.

Key benefits of combustion-based systems include: more reliable pathogen elimination compared to biological processes, significant reduction in waste volume (up to 90%), production of biochar or ash that can be safely disposed of in gardens or trash, scalability from single-household units to building-level systems, reduced dependence on environmental conditions compared to composting.

The Gates Foundation's approach incorporates energy recovery systems to minimize external power requirements, though these systems still typically require more energy input than passive composting or dehydration approaches. This energy requirement represents a potential limitation for applications in resource-constrained settings without reliable electricity access [1].

Reference [9] addressed this challenge by developing energy-autonomous technologies for public toilets,

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demonstrating that integrated renewable energy systems could support combustion-based treatment while minimizing external energy requirements. Their prototype achieved energy self-sufficiency through a combination of solar photovoltaics, small-scale wind turbines, and energy recovery from waste treatment processes, suggesting a pathway toward more sustainable implementation of these advanced systems.

4) Chemical Treatment Approaches

Chemical treatment of human waste in dry toilet systems has received renewed attention, particularly for applications requiring rapid pathogen inactivation. The Modiwell dry flush toilet system, for example, incorporates a coagulant in its waste treatment process to enhance containment and prevent leakage [6]. While specific formulations are proprietary, such coagulants typically function by binding liquid components and forming a gel-like substance that encapsulates solid waste.
Reference [17] investigated water-safe concepts for infection control in healthcare settings, including chemical approaches to pathogen inactivation. Their research demonstrated that targeted chemical treatments could achieve rapid pathogen reduction without the environmental concerns associated with broad-spectrum disinfectants. These findings have implications for dry toilet technologies, suggesting potential for more selective and environmentally responsible chemical treatment approaches.
Other chemical approaches include alkaline treatment (typically using lime or ash to raise pH above 12), acidification (lowering pH to inhibit pathogen survival), and oxidation (using peroxides or other oxidizing agents to destroy organic compounds and pathogens). These approaches offer rapid treatment but may introduce concerns regarding chemical residues and environmental impacts of treated waste [16].

The reference [21] provided comprehensive guidance on water and sanitation technologies for healthcare facilities, including chemical treatment approaches for human waste. Their recommendations emphasized the importance of selecting treatment chemicals that achieve pathogen inactivation while minimizing environmental and health risks, noting that "chemical selection should consider not only efficacy against target pathogens but also worker safety, environmental fate, and compatibility with subsequent waste management processes".

5) Integrated Treatment Systems

Reference [22] developed a pilot-scale system for phosphorus recovery from mobile toilet wastewater in rural areas, demonstrating that even small-scale, decentralized systems could achieve effective nutrient extraction. Their approach combined physical separation, chemical precipitation, and biological treatment to recover up to 85% of phosphorus in forms suitable for agricultural application. This integrated approach exemplifies the trend toward multifunctional treatment systems that address both sanitation needs and resource recovery objectives.

6) Comparative Analysis of Treatment Approaches

Table 2 presents an expanded comparative analysis of the major waste treatment approaches discussed above.
This expanded comparison highlights the diversity of treatment options available for dry toilet systems, with selection depending on specific priorities such as treatment speed, pathogen reduction, nutrient recovery, energy availability, and intended end use of treated waste. The emergence of integrated systems combining multiple treatment approaches represents a promising direction for optimizing performance across multiple criteria.

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Table 2. Characteristics of waste treatment approaches.

Feature	Composting	Dehydration	Combusti on	Chemical Treatment	Integrated Systems
Treatment Time	Weeks to months	Days to weeks	Minutes to hours	Minutes to days	Variable (process-dependent)
Pathogen Reduction	High (with proper management)	Moderate to high	Very high	High	High to very high
Volume Reduction	Moderate (40-60%)	Moderate (50-70%)	Very high (80-90%)	Low to moderate	High (70-80%)
Energy Requirements	Low (passive systems)	Low to moderate	High	Low	Moderate
Nutrient Preservation	High	Moderate	Low	Variable	Very high
Complexity	Moderate	Low	High	Low	High
Sensitivity to Environmental Conditions	High	Moderate	Low	Low	Moderate
End Product	Compost	Dried waste	Ash/bioch ar	Chemically stabilized waste	Multiple (process-dependent)
Resource Recovery Potential	High	Moderate	Moderate (biochar)	Low to moderate	Very high
Scalability	Limited by space	Good	Very good	Very good	Moderate
Cost	Low to moderate	Low	High	Low to moderate	High

D. Pathogen Elimination and Safety Considerations

Ensuring effective pathogen elimination is paramount in dry toilet technologies to protect public health and enable safe waste management. Recent research has advanced our understanding of microbial risks, inactivation mechanisms, testing methodologies, and regulatory frameworks.

1) Microbial Risks in Human Waste

Human excrement contains numerous potential pathogens, including bacteria (e.g., Salmonella, E. coli), viruses (e.g., norovirus, hepatitis A), protozoa (e.g., Cryptosporidium, Giardia), and helminths (parasitic worms). The concentration and viability of these pathogens vary depending on factors such as local disease prevalence, individual health status, and environmental conditions [2].

Reference [16] highlighted particular concerns regarding antimicrobial-resistant organisms in human waste, noting that traditional sanitation systems can serve as reservoirs and transmission routes for these organisms. Their research in Nairobi's Kibera slums demonstrated that pit latrines frequently contained antimicrobial-resistant bacteria, potentially contributing to the spread of resistance genes in the environment. This finding underscores the importance of effective pathogen elimination in dry toilet systems, not only for immediate disease prevention but also for addressing broader public health challenges such as antimicrobial resistance.

Reference [20] conducted extensive research on pathogen transmission through water, feces, and contaminated surfaces, developing quantitative models to predict pathogen survival and transport under different environmental conditions. Her work demonstrated that pathogen behavior varies significantly across different classes of organisms, with implications for treatment system design. For example, while bacteria are generally sensitive to desiccation and thermal treatment, protozoan cysts and helminth eggs may require more intensive or prolonged treatment for effective inactivation.

Reference [17] investigated polymicrobial outbreaks in healthcare settings, finding that water-safe concepts, including waterless hygiene approaches, were effective in controlling transmission of carbapenemase-producing Enterobacterales. Their research has implications for dry toilet technologies, suggesting that properly designed waterless systems may offer advantages for pathogen containment in certain contexts.

2) Temperature and pH Requirements for Pathogen Inactivation

Reference [19] expanded on this work, using multi-omics approaches to characterize microbial community dynamics during composting. Their research identified specific microbial taxa and metabolic pathways associated with pathogen suppression, suggesting potential for bioengineering more effective composting systems. The authors noted that "understanding the molecular mechanisms of pathogen suppression could enable development of targeted inoculants or process modifications to enhance safety assurance in composting systems".

pH manipulation offers another approach to pathogen inactivation. Alkaline conditions (pH > 9) inhibit most bacterial pathogens and accelerate the die-off of viruses and protozoa. Traditional practices of adding ash or lime to dry toilets leverage this mechanism. Conversely, acidic conditions (pH < 4) can also inactivate many pathogens but may be less practical for typical dry toilet applications due to material compatibility issues and potential odor concerns [16].

The Environmental Science and Research (ESR) report on Legionella in recycled wastewater and greywater [23] provided valuable insights regarding pathogen survival under different treatment conditions. The report noted that while most enteric pathogens are relatively sensitive to environmental stressors, opportunistic pathogens like Legionella may persist or even proliferate in certain treatment systems, highlighting the importance of comprehensive risk assessment and targeted control measures.

3) Sealing Mechanisms for Pathogen Containment

Physical containment through sealing mechanisms represents a complementary approach to pathogen management in dry toilet systems. The CompoCloset S1 Sealing Toilet exemplifies this approach with its "powerful sealing mechanism that locks away solid waste after every use" [4]. By physically isolating waste from human contact and environmental exposure, such systems reduce transmission risks even before complete pathogen inactivation occurs.

Similarly, the Modiwell dry flush toilet system employs "garbage bags effectively sealed" with a coagulant to prevent leakage [6]. This approach combines physical containment with chemical treatment to enhance safety during the handling and disposal of waste.

The World Bank's evaluation of container-based sanitation noted that "a waterless flush helps to seal urine and feces in biodegradable polymer film in a plastic container, which, once full, is collected and hand-delivered to processing facilities" [7]. This approach has proven effective in urban informal settlements where conventional sewerage is impractical, offering a scalable solution that addresses both user experience and public health protection.

Reference [24] reported on waterless bathing and infection control in healthcare settings, demonstrating that minimizing water use can effectively reduce risks associated with waterborne infections. Their approach emphasizes physical containment of potentially infectious materials, with implications for dry toilet technologies in both healthcare and community settings.

4) Testing and Validation Methods

Reference [19] demonstrated the value of multi-omics approaches - combining genomics, transcriptomics, proteomics, and metabolomics - for characterizing microbial communities and functional activities in composting systems. Their research highlighted how these advanced techniques can identify not only which

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microorganisms are present but also their metabolic activities and interactions, providing deeper insights into pathogen suppression mechanisms and treatment efficacy.

Reference [20] developed innovative approaches for detecting and quantifying pathogens in environmental samples, including PCR-based methods capable of distinguishing between viable and non-viable organisms. Her research demonstrated that traditional culture-based methods may underestimate pathogen persistence in treated waste, highlighting the importance of advanced detection techniques for comprehensive safety assessment.

5) Regulatory Standards and Guidelines

Regulatory frameworks for dry toilet systems vary considerably across jurisdictions, reflecting differences in risk perception, technological familiarity, and governance structures. In many regions, regulations developed for conventional sanitation systems have been adapted for dry toilets, sometimes resulting in requirements poorly aligned with the specific characteristics of waterless technologies.

The World Health Organization's "Guidelines for the Safe Use of Wastewater, Excreta and Greywater" provides a risk-based framework applicable to dry toilet systems, particularly regarding the agricultural reuse of treated waste. These guidelines emphasize a multiple-barrier approach to risk management, recognizing that no single intervention can ensure complete safety across all contexts [2].

The WHO's more recent guidance on water and sanitation technologies for healthcare facilities [21] includes specific considerations for waterless and low-water sanitation systems, acknowledging their potential advantages in water-scarce or infrastructure-limited settings. This guidance emphasizes the importance of context-specific risk assessment and management approaches rather than prescriptive technological requirements.

Reference [25] highlighted the importance of addressing regulatory regimes to scale up adoption of urine source separation technologies. Their analysis demonstrated that existing regulatory frameworks often create barriers to innovation in sanitation, emphasizing the need for performance-based rather than technology-based standards to enable wider implementation of alternative approaches.

E. Nutrient Recovery and Reuse of Treated Human Solid Waste

Human excrement contains valuable nutrients, particularly nitrogen, phosphorus, and potassium, that can be recovered and reused through appropriate treatment processes. Recent research has advanced our understanding of nutrient content, recovery technologies, agricultural applications, and quality standards for treated waste.

1) Nutrient Content of Human Waste

The nutrient composition of human waste varies depending on diet, age, health status, and other factors. Urine typically contains the majority of nitrogen and potassium, while feces contain most of the phosphorus and organic matter. This distribution underlies the logic of urine-diverting systems, which facilitate targeted recovery of different nutrient fractions [2].

Reference [26] conducted a comprehensive analysis of the opportunities and challenges of using human excreta-derived fertilizers (HEDFs). Their research quantified nutrient content and availability across different treatment processes, finding that while nutrient concentrations varied considerably, properly treated human waste could provide significant proportions of crop nutrient requirements. The authors noted that "the nutrient value of human excreta is often under-appreciated, with each person producing fertilizer equivalent to approximately 50% of their food production requirements".

Reference [27] examined the potential for improving nutrient use efficiencies in human food systems, highlighting the significant losses that occur throughout the food-waste-excreta cycle. Their analysis demonstrated that recovering nutrients from human waste could reduce synthetic fertilizer requirements by 15-25% globally, with even higher potential in regions with limited access to commercial fertilizers.

2) Recovery Technologies and Processes

Various technologies and processes have been developed for nutrient recovery from human waste, with recent innovations focusing on efficiency, safety, and practicality. Composting remains one of the most widely applied approaches, transforming organic matter into stable humus while preserving most nutrients in plant-available forms.

Reference [22] developed a pilot-scale system for phosphorus recovery from mobile toilet wastewater through struvite formation. Their research demonstrated recovery efficiencies of 75-85% under optimized conditions, producing crystalline struvite suitable for direct agricultural application. The authors noted that "small-scale, decentralized recovery systems can achieve performance comparable to industrial-scale processes while offering greater flexibility for implementation in diverse contexts".

Reference [25] examined regulatory barriers to scaling up urine source separation technologies, noting that despite proven technical feasibility, institutional and regulatory constraints often limit implementation. Their research emphasized the need for policy frameworks that recognize and value the resource recovery potential of human waste, particularly regarding phosphorus as a critical and finite resource.

The Gates Foundation's combustion-based systems represent a different approach to waste treatment, prioritizing pathogen elimination and volume reduction over nutrient recovery. While these systems convert most organic nitrogen to gaseous forms (lost during combustion), they concentrate phosphorus and potassium in the resulting biochar or ash, which can still serve as a valuable soil amendment [1].

Reference [8] provided a comprehensive life cycle assessment (LCA) comparing Sol-Char and anaerobic digestion systems, examining energy usage, pathogen elimination, and sustainability trade-offs.

3) Agricultural Applications

Reference [26] conducted a comprehensive review of opportunities and challenges in using human excreta-derived fertilizers, finding that "properly treated HEDFs can match or exceed the performance of conventional fertilizers for many crops". Their analysis of 87 field studies across different geographical contexts demonstrated consistent yield benefits, particularly in nutrient-limited agricultural systems. However, the authors also noted challenges regarding nutrient availability timing, potential contaminants, and social acceptance.

Reference [27] reviewed several technologies for processing food and human waste streams, including anaerobic digestion, hydrothermal carbonization, and composting. Their analysis highlighted the varying nutrient preservation efficiencies across different processes, with implications for selecting appropriate treatment approaches based on intended end uses and local agricultural needs.

4) Non-Agricultural Applications

Beyond agriculture, reference [28] explored innovative non-fertilizer applications of treated human waste. Their review highlighted emerging opportunities in construction materials (e.g., biochar-enhanced concrete), energy production (e.g., biogas generation), and environmental remediation (e.g., using biochar for soil contaminant immobilization). These alternative applications may be particularly valuable in contexts where agricultural use faces cultural resistance or regulatory barriers.

The production of biochar from human waste through pyrolysis or combustion processes offers multiple benefits: it eliminates pathogens, reduces volume, stabilizes carbon (potentially contributing to carbon sequestration), and creates a product with applications in agriculture, construction, and environmental management. The Gates Foundation's combustion-based toilet systems leverage these benefits, producing biochar or ash that can be "disposed of safely in the garden or the trash" [1].

Reference [8] evaluated the environmental performance of Sol-Char sanitation systems, noting that the biochar produced had potential applications beyond agriculture, including carbon sequestration, water filtration, and soil remediation. Their life cycle assessment demonstrated that considering these multiple value streams significantly improved the overall sustainability profile of thermal treatment approaches.

5) Quality Standards and Safety Considerations

The World Health Organization's "Guidelines for the Safe Use of Wastewater, Excreta and Greywater" provides a risk-based framework that has informed many national and regional standards. These guidelines recognize different levels of treatment corresponding to different end uses, with more stringent requirements for applications with higher exposure potential [2].

Reference [26] reviewed quality standards for human excreta-derived fertilizers across different jurisdictions, noting significant variations in both parameters and threshold values. Their analysis highlighted the need for harmonized, science-based standards that address legitimate safety concerns without creating unnecessary barriers to resource recovery and utilization.

Emerging concerns regarding pharmaceutical residues, microplastics, and antimicrobial resistance genes present new challenges for quality assurance. Reference [16] highlighted the potential for pit latrines and other sanitation systems to serve as reservoirs for antimicrobial-resistant organisms, suggesting that advanced treatment processes may be necessary to address these emerging contaminants of concern.

Reference [20] developed innovative approaches for detecting and quantifying pathogens and contaminants in environmental samples, including methods capable of distinguishing between different sources of contamination. Her research has implications for quality assurance in nutrient recovery systems, potentially enabling more targeted and effective monitoring approaches.

F. Environmental Impact and Sustainability Assessment

The environmental impact of dry toilet technologies extends beyond water conservation to include considerations of energy use, greenhouse gas emissions, resource recovery, and lifecycle impacts. Recent research has advanced our understanding of these dimensions and provided frameworks for comprehensive sustainability assessment.

1) Water Conservation Benefits

Reference [6] designed compact dry flush systems, emphasizing portability and environmental compliance.

Reference [5] reported that their Optima 7 vacuum toilet achieves 90% water savings compared to traditional gravity toilets, demonstrating that even systems using minimal water can offer substantial conservation benefits. Their sustainability report emphasized that "water efficiency is no longer optional but essential for future-proofing sanitation systems against climate change impacts and resource constraints".

Quantitative assessments of water savings from dry toilet implementation vary depending on comparison baselines and usage patterns. Reference [29] estimated that replacing conventional toilets with dry alternatives could reduce household water consumption by 25-35%, with corresponding reductions in wastewater generation and treatment requirements.

Reference [3] reviewed dry toilet technologies with particular attention to their water conservation benefits in water-scarce regions. Their analysis demonstrated that beyond direct water savings, dry toilets reduce pressure on water resources by eliminating contamination risks to groundwater and surface water, thereby preserving water quality alongside quantity.

2) Energy Requirements and Greenhouse Gas Emissions

Energy requirements represent another important dimension of environmental impact. Different dry toilet technologies exhibit varying energy profiles, from passive composting systems requiring minimal external energy to combustion-based systems with higher energy demands for thermal processing. The Gates Foundation's combustion-based systems, while energy-intensive compared to passive alternatives, incorporate energy recovery mechanisms to minimize net requirements. These systems prioritize pathogen elimination and waste volume reduction over minimal energy use, reflecting a design philosophy that values public health protection alongside environmental considerations [1].

Reference [8] conducted a comparative life cycle analysis of Sol-Char and anaerobic digestion sanitation systems, finding that while Sol-Char systems had higher direct energy inputs, their superior pathogen elimination and reduced transportation requirements resulted in comparable overall energy profiles when considering the complete system boundary. The authors noted that "energy assessment must consider not only direct inputs but also avoided impacts and system-wide effects".

Reference [9] developed energy-autonomous technologies for public toilets, demonstrating that integrated renewable energy systems could support even energy-intensive treatment processes while minimizing external requirements. Their prototype achieved energy self-sufficiency through a combination of solar photovoltaics, small-scale wind turbines, and energy recovery from waste treatment processes, suggesting a pathway toward more sustainable implementation of advanced systems.

Battery-powered systems such as the CompoCloset S1 (50 flushes per charge) and Modiwell dry flush toilet (70-100 uses per charge) represent intermediate energy profiles. These systems require periodic recharging but offer greater portability and independence from fixed infrastructure compared to combustion-based alternatives [4] and [6].

3) Life Cycle Assessment Approaches

Life cycle assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of dry toilet technologies across their entire lifecycle, from raw material extraction through manufacturing, use, and end-of-life management. Reference [29] reviewed LCA studies comparing conventional and alternative sanitation systems, noting methodological challenges including system boundary definition, functional unit selection, and impact allocation.

Reference [8] applied LCA methodology to compare Sol-Char and anaerobic digestion sanitation systems, evaluating impacts across multiple environmental categories including global warming potential, eutrophication, acidification, and resource depletion. Their analysis demonstrated the importance of context-specific assessment, with relative performance varying depending on local energy sources, transportation distances, and end-use applications for recovered resources.

Reference [30] conducted a techno-economic and environmental impact assessment of membrane bioreactor technology for wastewater treatment, providing valuable methodological insights applicable to dry toilet systems. Their research emphasized the importance of considering both direct impacts and avoided burdens when evaluating alternative sanitation approaches, particularly regarding nutrient recovery and water conservation benefits.

Reference [31] conducted an environmental sustainability assessment of tissue paper production, with findings relevant to the material aspects of dry toilet systems. Their research highlighted the significant environmental impacts associated with conventional paper products, suggesting that biodegradable alternatives developed for dry toilet applications could offer broader sustainability benefits if adopted in related product categories.

These studies identified several consistent findings across LCA studies: dry toilet systems typically demonstrate lower water consumption and eutrophication potential compared to conventional alternatives; energy requirements vary significantly depending on technology type and management practices; the environmental benefits of nutrient recovery depend on displacement of synthetic fertilizer production; transportation impacts can be significant for systems requiring regular collection and centralized treatment; user behavior and maintenance practices substantially influence actual environmental performance.

These findings highlight the importance of context-specific assessment rather than universal claims about environmental superiority. The optimal system from an environmental perspective depends on local conditions including water availability, energy sources, transportation infrastructure, and waste management options.

4) Material Considerations and Circular Economy

Material selection and waste management approaches in dry toilet technologies increasingly reflect circular economy principles, aiming to minimize resource consumption and waste generation while maximizing recovery and reuse. The development of biodegradable materials for toilet applications exemplifies this trend, with innovations such as Modiwell's compostable garbage bags (compliant with European Union EN 13432 standards) and Laveo's sugarcane bagasse cartridges representing steps toward closed-loop systems [6].

Reference [16] explicitly framed their research on pit latrine alternatives in terms of circular economy principles, advocating for systems that recover resources while minimizing environmental contamination. Their work highlighted the potential for innovative dry toilet technologies to address multiple environmental challenges simultaneously, from water conservation and waste reduction to resource recovery and pollution prevention.

Reference [32] examined leveraging a sanitation value chain framework to improve China's Toilet Revolution, emphasizing the importance of considering the entire system from waste generation through collection, treatment, and end-use applications. Their research demonstrated that fragmented approaches focusing on individual components often fail to achieve optimal environmental outcomes, highlighting the need for integrated, systems-based strategies.

The Gates Foundation's combustion-based systems similarly reflect circular thinking, with their emphasis on water recycling for non-potable reuse and biochar production for soil amendment. By recovering both water and nutrients from waste streams, these systems reduce external resource requirements while providing valuable outputs [1].

Reference [14] developed mechanically tunable, compostable, healable, and scalable engineered living materials with potential applications in degradable films for toilet systems. Their innovative approach exemplifies circular economy principles by designing materials that not only minimize environmental impact during production and use but also contribute positively to biological systems after disposal.

5) Comparison with Conventional Sanitation Systems

Comparative assessments of dry toilet technologies against conventional alternatives reveal complex trade-offs across different environmental impact categories. Reference [29] synthesized findings from multiple studies, noting that dry systems typically outperform conventional alternatives in water consumption, eutrophication potential, and aquatic ecotoxicity, while performance in energy use, greenhouse gas emissions, and land use varies depending on specific technologies and implementation contexts.

Reference [3] conducted a comprehensive review of dry toilet management approaches, comparing environmental performance across different system types and geographical contexts. Their analysis demonstrated that while all dry systems offer water conservation benefits, their overall environmental profiles vary considerably depending on design, management practices, and local conditions.

Table 3 presents an expanded comparison of key environmental performance indicators across different sanitation approaches based on these studies. This expanded comparison highlights the context-dependent nature of environmental performance and the importance of prioritizing impact categories based on local conditions and values. In water-stressed regions, the water conservation benefits of dry systems may outweigh other considerations, while in energy-constrained contexts, passive composting systems might be preferable despite their larger land requirements.

G. Social Acceptance and Implementation Challenges

The technical feasibility of dry toilet technologies ultimately matters little without social acceptance and practical implementation pathways. Recent research has advanced our understanding of user perceptions, cultural factors, economic considerations, and policy frameworks that influence adoption and sustained use.

1) User Perceptions and Preferences

Recent product innovations reflect growing attention to user experience factors. The CompoCloset S1 Sealing Toilet, for example, emphasizes features addressing common user concerns: urine diversion to reduce odor, a powerful sealing mechanism for waste containment, and a compact, portable design suitable for various applications [4]. Similarly, the Modiwell dry flush toilet highlights its lightweight, foldable design and odor control capabilities as key selling points [6].

Reference [11] specifically investigated user-centered design considerations for disposable toilet seat covers, noting that beyond functional requirements (disintegration efficiency, water resistance), user comfort and perception significantly influence acceptance. Their research incorporated both technical performance metrics and user experience factors, exemplifying the integrated approach necessary for successful innovation in this field.

Reference [33] conducted a case study on perceptions and attitudes toward eco-toilet systems in rural areas of the Philippines, finding that social acceptance remains a key barrier to deployment despite technical feasibility. Their research identified several factors influencing acceptance, including perceived convenience, aesthetics, odor concerns, and cultural taboos surrounding human waste. The authors

Table 3. Environmental performance indicators for different sanitation approaches.

Environmental Indicator	Conventional Flush Toilets	Composting Toilets	Urine-Diverting Dry Toilets	Packaging Systems (Modiwell)	Combustion-Based Systems
Water Consumption	High	Very Low	Very Low	Very Low	Low
Energy Use	Moderate (treatment)	Low	Low	Low to Moderate (battery)	High
Greenhouse Gas Emissions	Moderate to High	Low to Moderate	Low	Low	Moderate
Eutrophication Potential	High	Low	Very Low	Low	Low
Resource Recovery	Limited	High	Very High	Low	Moderate
Land Requirements	High (treatment)	Moderate	Moderate	Low	Low
Aquatic Ecotoxicity	High	Low	Low	Low	Very Low
Material Intensity	Moderate	Low to Moderate	Moderate	High (consumables)	High (infrastructure)
Circular Economy Alignment	Low	Moderate	High	Moderate	Moderate
Climate Resilience	Low	High	High	High	Moderate

emphasized that "technical solutions must be complemented by culturally sensitive engagement strategies that address both practical and psychological barriers to adoption".
The reference [34] explored the concept of toilets as "a place for peace", examining how ancient wisdom and modern aesthetics can reshape perceptions of this essential facility. Their analysis noted that "as of 2023, over 1.5 billion people still lack access to basic sanitation services", emphasizing the need to transform perceptions of toilets from "dirty or unsafe spaces to dignified, essential facilities". This perspective highlights the importance of addressing psychological and cultural dimensions alongside technical performance in promoting dry toilet adoption.

2) Cultural and Behavioral Factors

Reference [16] highlighted the complex interplay between cultural factors and sanitation practices in their study of Nairobi's Kibera slums. They noted that successful interventions required not only appropriate technologies but also engagement with community values, existing practices, and social structures. Their research emphasized the importance of participatory approaches that involve users in technology selection and adaptation rather than imposing external solutions.
Reference [35] investigated barriers to transition to resource-oriented sanitation in rural Ethiopia, identifying cultural taboos, religious beliefs, and traditional practices as significant factors influencing acceptance. Their research demonstrated that even technically sound and economically viable solutions may fail if they conflict with deeply held cultural values or established behavioral patterns. The authors emphasized the need for "culturally grounded implementation strategies that respect local knowledge systems while introducing beneficial innovations".
Reference [36] examined neglected second and third generation challenges of urban sanitation, arguing that "sanitation systems often reproduce and exacerbate existing societal hierarchies and discriminations in terms of unequal access to safely managed services". Their research highlighted how technological solutions must be complemented by attention to social equity and inclusion to achieve sustainable impact, particularly for marginalized communities.
Behavioral change represents another critical dimension of implementation. Even well-designed technologies may fail if they require unfamiliar behaviors without adequate support for transition. Reference [29] reviewed behavior change approaches in sanitation interventions, noting that successful programs typically combine infrastructure provision with education, demonstration, and ongoing support. They emphasized the importance of addressing both conscious decision-making factors (knowledge, attitudes) and unconscious influences (habits, social norms) in promoting sustained adoption.
The Economist Impact report on "Putting children first: tackling Toilet Loss in schools" [37] highlighted that globally, "427 million children go to school each day without a toilet that they can use". The report emphasized that the issue extends beyond toilet availability to include maintenance, privacy, safety, and cultural appropriateness. These findings underscore the importance of considering diverse user needs and contextual factors in dry toilet design and implementation, particularly for vulnerable populations.

3) Economic Considerations and Business Models

To address this challenge, the foundation outlined a market-based strategy: "focus on markets that have the resources and motivation to adopt new, more expensive technologies. This, in turn, will lead to greater demand and large-scale manufacturing and ultimately drive down the product cost for all markets" [1]. This approach parallels development pathways in other technologies, from solar panels to mobile phones, where initial adoption in higher-income markets enabled scale economies that eventually reduced costs for broader accessibility.
Reference [32] evaluated operational, financial, and management challenges within China's Toilet Revolution by surveying 656 rural households across 10 provinces. Their research identified several economic barriers to adoption, including high initial costs, limited financing options, and uncertain return on investment. The authors noted that "barriers to recycling human excreta include inadequate technology, prohibitive costs, and odor issues, rendering the sale of toilet products economically unviable in many contexts". These findings highlight the importance of developing cost-effective solutions and supportive financing mechanisms to enable broader adoption.
Beyond purchase price, economic considerations include ongoing operational costs, maintenance requirements, and potential revenue streams from recovered resources. Reference [29] reviewed various business models for sustainable sanitation, including service-based approaches (where providers maintain ownership of equipment and charge for services), resource recovery models (where value from recovered nutrients or energy offsets costs), and hybrid approaches combining multiple revenue streams.
Reference [38] examined advancements and challenges in decentralized wastewater treatment, noting that "despite these advantages, implementing decentralized systems still faces challenges. These include technological limitations, social and institutional factors, and economic constraints". Their analysis emphasized the importance of developing business models that distribute costs and benefits equitably across stakeholders, potentially through public-private partnerships or cooperative ownership structures.

4) Policy and Regulatory Frameworks

The foundation identified the United States and France as promising early adopter markets partly due to their "strong regulatory environments that not only require replacement of outdated septic tanks but also encourage adoption of environmentally friendly measures" [1]. These regulatory frameworks create market opportunities for innovative technologies that can demonstrate compliance with performance standards while offering environmental advantages over conventional alternatives.
Reference [25] examined how regulatory regimes influence the adoption of urine source separation technologies, finding that existing frameworks often create barriers to

innovation despite the proven benefits of these approaches. The authors argued that "researchers must address regulatory regimes to scale up adoption", emphasizing the need for science-based advocacy to inform policy development and create enabling environments for sustainable sanitation solutions.

Regulatory approaches to dry toilet technologies vary considerably across jurisdictions, reflecting differences in governance structures, technical capacity, and risk perception. Reference [29] categorized regulatory frameworks along a spectrum from prescriptive (specifying particular technologies or design parameters) to performance-based (establishing outcome requirements without dictating specific approaches). They noted a general trend toward performance-based regulation in higher-income countries, creating more space for innovation while maintaining public health protection.

Reference [39] examined the persistence of failure in water, sanitation, and hygiene programming, noting that "despite global progress towards universal WASH, much of WASH programming continues to fail to improve health outcomes or be sustainable in the longer term". Their analysis identified regulatory fragmentation and policy inconsistency as contributing factors, emphasizing the need for coherent, integrated governance approaches that align incentives across sectors and stakeholders.

5) Case Studies of Successful Implementation

Case studies of successful dry toilet implementation provide valuable insights into overcoming adoption barriers. The reference [1] strategic focus on the United States and France as early adopter markets represents one approach: targeting contexts where regulatory support, environmental awareness, and economic resources align to create favorable conditions for innovation.

Reference [16] described community-based initiatives in Nairobi's Kibera slums, where eco-friendly portable toilets have been introduced as alternatives to conventional pit latrines. Their case study highlighted the importance of community engagement, appropriate business models (including micro-finance options), and integration with existing waste management systems for successful implementation.

Reference [32] analyzed China's Toilet Revolution initiative, identifying both successes and challenges in this large-scale effort to transform rural sanitation. Their research demonstrated the importance of adapting implementation approaches to local conditions, with successful projects characterized by strong local leadership, appropriate technology selection, and sustained support for operation and maintenance.

Reference [33] documented a successful eco-toilet implementation in rural Philippines, emphasizing the role of participatory design processes and culturally sensitive education campaigns in overcoming initial resistance. Their case study demonstrated that "when users are engaged as co-designers rather than passive recipients, both technical solutions and adoption rates improve significantly".

Across diverse contexts, common success factors emerge from implementation case studies: technologies adapted to local conditions and user preferences, stakeholder engagement throughout planning and implementation, clear value proposition for users (convenience, status, cost savings), supportive policy environment or strategic navigation of regulatory constraints , sustainable financing mechanisms for both initial investment and ongoing operation, technical support systems for maintenance and troubleshooting, and integration with broader waste management and resource recovery systems.

These factors underscore the multidimensional nature of successful implementation, requiring attention to technical, social, economic, and institutional dimensions rather than narrow focus on technology development alone. As reference [36] noted, addressing "neglected second and third generation challenges of urban sanitation" requires moving beyond technical solutions to engage with the complex social, cultural, and political contexts in which sanitation systems operate.

IV. DISCUSSION

This comprehensive review of dry toilet technologies reveals a dynamic field characterized by significant innovation across multiple dimensions: toilet design, degradable materials, waste treatment processes, pathogen elimination, nutrient recovery, environmental impact, and social acceptance. Several key patterns, contradictions, and research gaps emerge from this synthesis of recent literature.

A. Synthesis of Key Findings

The review demonstrates substantial technological advancement in dry toilet systems over the past three years. Innovations such as the CompoCloset S1 Sealing Toilet and Modiwell dry flush toilet represent significant improvements in user experience without compromising environmental benefits. These systems address historical barriers to adoption - particularly odor, convenience, and aesthetics - while maintaining core sustainability advantages of waterless approaches. Similarly, the Gates Foundation’s combustion-based systems offer promising alternatives for contexts where rapid waste treatment and volume reduction are prioritized over nutrient recovery.

Materials science advances have yielded promising developments in degradable films for toilet applications. Reference [11] work on cellulose-based toilet seat covers with optimized disintegration properties exemplifies the potential for materials that balance durability during use with degradability after disposal. The integration of antimicrobial properties without compromising environmental credentials represents another important advancement, particularly relevant in the post-pandemic context of heightened hygiene awareness.

Waste treatment approaches have diversified beyond traditional composting to include innovations in dehydration, combustion, and chemical treatment. Reference [2] review of microbiome science in human excrement composting highlights how advanced analytical techniques are enhancing our understanding of treatment processes, potentially enabling more efficient and reliable pathogen elimination. The Gates Foundation's focus on combustion-based systems represents a significant departure from biological treatment approaches, offering advantages in treatment speed, pathogen elimination, and volume reduction at the cost of higher energy requirements and reduced nutrient recovery.

Environmental impact assessments reveal complex trade-offs across different technology types and impact categories. While all dry toilet systems offer water conservation benefits compared to conventional alternatives, their performance in energy use, greenhouse gas emissions, and resource recovery varies considerably.

Reference [29] review of life cycle assessment studies emphasizes the importance of context-specific evaluation rather than universal claims about environmental superiority. Social acceptance and implementation challenges remain significant despite technological advances. The reference [1] acknowledgment that cost represents "the biggest challenge" for reinvented toilets highlights the tension between technological sophistication and affordability. Their market-based strategy - focusing initially on higher-income markets to drive scale economies before broader dissemination - represents one approach to addressing this challenge, though questions remain about its effectiveness for reaching the most vulnerable populations.

B. Patterns, Contradictions, and Gaps

Several patterns emerge across the reviewed literature. First, there is increasing recognition of the need for user-centered design approaches that address aesthetic and experiential factors alongside technical performance. Second, material innovations increasingly balance multiple requirements - durability, degradability, antimicrobial properties - rather than optimizing for single parameters. Third, waste treatment approaches are diversifying beyond traditional composting to include thermal, chemical, and hybrid processes tailored to different contexts and priorities.

Contradictions and tensions are also evident. The Gates Foundation's emphasis on combustion-based systems prioritizes pathogen elimination and volume reduction over nutrient recovery, while other approaches such as urine-diverting composting toilets emphasize resource recovery as a primary benefit. These divergent priorities reflect different underlying values and assumptions about the primary purpose of sanitation systems: waste elimination versus resource recovery.

Similarly, tensions exist between technological sophistication and affordability, particularly for reaching lower-income populations most affected by inadequate sanitation. The Gates Foundation's market-based strategy assumes that initial adoption in higher-income markets will eventually reduce costs for broader accessibility, but this pathway may be lengthy and uncertain. Alternative approaches emphasizing simpler, lower-cost technologies with incremental improvements might reach vulnerable populations more quickly, though potentially with fewer performance benefits.

Several significant research gaps emerge from this review:

1. Long-term performance data: Most innovations discussed are relatively recent, with limited evidence regarding long-term performance, durability, and user satisfaction. Longitudinal studies tracking technology performance and user experience over extended periods would provide valuable insights for future development.
2. Comparative effectiveness studies: While individual technologies have been evaluated against conventional alternatives, few studies directly compare different dry toilet approaches under standardized conditions. Such comparisons would enhance understanding of relative advantages and appropriate contexts for different technologies.
3. Degradable materials optimization: Despite promising advances in cellulose-based materials and biodegradable polymers, further research is needed to optimize degradable films specifically for toilet applications, balancing water resistance during use with rapid degradation after disposal.
4. Pharmaceutical and micro-pollutant management: Limited research addresses the fate of pharmaceuticals, personal care products, and other micro-pollutants in dry toilet systems. Given increasing concerns about these contaminants in conventional wastewater treatment, understanding their behavior in alternative systems is increasingly important.
5. Implementation science: While technical aspects of dry toilet technologies are well-studied, research on effective implementation strategies, behavior change approaches, and business models remains limited, particularly for diverse cultural and economic contexts.
6. Policy and regulatory frameworks: Few studies systematically analyze how policy and regulatory environments influence dry toilet adoption and implementation. Comparative policy analysis could identify effective governance approaches for supporting sustainable sanitation transitions.

C. Importance of Continued Innovation

The continued development of dry toilet technologies remains critically important for addressing global sanitation challenges while conserving water resources and reducing environmental impacts. With approximately 3.5 billion people lacking access to safe sanitation [1] and growing water scarcity exacerbated by climate change, conventional water-based sanitation systems cannot sustainably meet global needs.

Innovations that enhance user experience while maintaining environmental benefits are particularly valuable for broadening adoption beyond environmentally motivated early adopters. The recent emphasis on aesthetic and experiential factors alongside technical performance represents an important shift toward more user-centered design approaches that could accelerate adoption across diverse contexts.

Material innovations, particularly degradable films balancing durability during use with degradability after disposal, offer significant potential for enhancing both user experience and environmental performance. Continued research in this area, building on recent advances in cellulose-based materials and biodegradable polymers, could yield solutions that overcome historical barriers to dry toilet adoption.

D. Future Research Directions

Several promising directions for future research emerge from this review:

1. Longitudinal studies tracking technology performance and user experience over extended periods to provide insights regarding long-term durability, satisfaction, and environmental impacts.
2. Comparative effectiveness studies directly comparing different dry toilet approaches under standardized conditions to

enhance understanding of relative advantages and appropriate contexts.

3. Advanced materials research focusing on optimizing degradable films specifically for toilet applications, potentially incorporating nanotechnology or biomimetic approaches to achieve seemingly contradictory properties.

4. Pharmaceutical and micro-pollutant fate studies examining the behavior of these emerging contaminants in different dry toilet systems and treatment processes.

5. Implementation science research investigating effective strategies for promoting adoption and sustained use across diverse cultural and economic contexts.

6. Policy and regulatory analysis identifying governance approaches that support sustainable sanitation transitions while ensuring public health protection.

7. Integrated assessment methodologies that simultaneously consider technical performance, user experience, environmental impacts, and economic factors to support better technology evaluation and development.

E. Methodological Limitation

Several methodological limitations should be acknowledged in this review. First, the focus on recent literature (2022-2025) provides current insights but may overlook valuable historical developments and longer-term trends. Second, the emphasis on English-language publications potentially excludes relevant research from non-English speaking regions. Third, access limitations for certain academic publications may have resulted in incomplete coverage of some research areas.

Additionally, the rapid pace of innovation in this field means that some recent developments may not yet be reflected in the academic literature, particularly those originating from commercial entities with limited incentives for public disclosure. Industry publications and patent filings provide some insight into these developments, but proprietary information restrictions likely result in incomplete coverage.

IV. CONCLUSION

This literature review has examined recent advancements in dry toilet technologies across seven key dimensions: current designs, degradable materials, waste treatment processes, pathogen elimination, nutrient recovery, environmental impact, and social acceptance. The review reveals a field characterized by significant innovation and diversification, with multiple approaches emerging to address different priorities and contexts.

Key findings include:

1. Recent innovations in dry toilet designs - such as the CompoCloset S1 Sealing Toilet, Modiwell dry flush toilet, and Gates Foundation combustion-based systems - have significantly improved user experience while maintaining environmental benefits.

2. Degradable materials research has advanced understanding of cellulose-based films with optimized disintegration properties, with reference [11] work demonstrating the potential for materials that balance water resistance during use with degradability after disposal.

3. Waste treatment approaches have diversified beyond traditional composting to include innovations in dehydration, combustion, and chemical treatment, offering different advantages in treatment speed, pathogen elimination, and resource recovery.

4. Pathogen elimination strategies increasingly combine multiple approaches - temperature, pH, physical containment, and chemical treatment - to ensure safety across diverse contexts and potential pathogens.

5. Nutrient recovery methods range from traditional composting (preserving most nutrients in plant-available forms) to innovative technologies for extracting specific nutrients from separated waste streams.

6. Environmental impact assessments reveal complex trade-offs across different technology types and impact categories, highlighting the importance of context-specific evaluation rather than universal claims about environmental superiority.

7. Social acceptance and implementation challenges remain significant despite technological advances, with cost representing a particular barrier for reaching vulnerable populations most affected by inadequate sanitation.

In conclusion, dry toilet technologies represent a promising approach to addressing global sanitation challenges while conserving water resources and reducing environmental impacts. Recent innovations have significantly improved user experience and technical performance, though challenges remain regarding cost, implementation, and social acceptance. By building on recent research and addressing identified gaps, such an innovation could contribute significantly to more sustainable and equitable sanitation systems worldwide.

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