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Review

Sustainable Water and Waste Systems for Resilient Housing in Canada

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Abstract

Sustainable water and solid waste systems are critical components of resilient building design, essential for addressing climate change, rapid urbanization, and resource scarcity. This study adopts a narrative and integrative review approach to synthesize contemporary practices, emerging technologies, and regulatory frameworks, with a particular focus on the Canadian and British Columbia context. Even though Canada possesses about 20% of the world's freshwater reserves, relatively high per capita consumption (the average is 286 L per day in British Columbia) and rising demand underscore the urgent need for conservation-oriented policies. This research explores decentralized strategies such as rainwater harvesting, greywater reuse, and on-site treatment to alleviate pressure on aging municipal infrastructure. It explores sustainable waste management by focusing on source separation, diversion programs, and the shift toward a circular economy. It emphasizes that achieving long-term sustainability in residential building requires addressing issues of equity, governance, and the incorporation of Indigenous knowledge. The findings indicate that a comprehensive approach, which includes innovative technologies, behavioral changes, supportive policies, and code updates, is essential for creating equitable and environmentally responsible systems in residential buildings. The key contribution of this review is its assessment of system thinking, focusing on technical performance, environmental resilience, governance, and equity, emphasizing the need for holistic approaches over isolated technological solutions.

Keywords: water supply; water conservation and treatment; household waste; sustainable waste management; circular economy; equity and resilience in water and waste systems

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1. Introduction

Water and solid waste systems are fundamental components of sustainable, environmentally friendly building designs, influencing building operations, environmental performance, and occupant well-being. Efficient water-use practices reduce reliance on potable water supplies and help mitigate growing concerns about water scarcity [1,2]. Similarly, effective waste management strategies decrease landfill reliance, promote material recovery, and reduce greenhouse gas (GHG) emissions [3,4]. When these systems are thoughtfully incorporated into building designs, they not only help reduce operating costs but also enhance building resilience to challenges such as flooding, drought, extreme rainfall, snowfall, and temperature variability. The development of sustainable water and waste systems is essential for advancing resilient, low-impact buildings capable of meeting future environmental and societal challenges.

The design of water and waste systems must explicitly account for climate and demographic changes, including increasing water shortages, heightened climate variability, and the growing demands driven by rapid urbanization [5,6]. The evolving climate often leads to more prolonged or intensive extreme weather events, such as severe droughts, heatwaves, heavy snow/ice buildup, and floods. These severe climate events can make it hard to access enough clean water and can also overwhelm wastewater treatment systems. Urbanization increases the demand for potable water and generates higher volumes of wastewater and solid waste, often stressing already aging municipal infrastructure. The relevance of wastewater reuse and consideration of the urban water cycle as a whole is fundamental here [7]. Sustainable water management strategies such as rainwater harvesting, greywater reuse, and decentralized wastewater treatment alleviate pressures by decreasing dependence on centralized water supply, conserving resources, and efficiently handling stormwater [8]. Simultaneously, sustainable solid waste management practices such as source reduction, recycling, composting, and reuse help alleviate pressure by reducing reliance on landfills, conserving raw materials, reducing GHG emissions, reclaiming value from waste, and supporting the circular economy [9]. By addressing these challenges, resilient water and solid waste systems contribute to environmental protection and the long-term sustainability of urban and rural communities.

1.1. Water Consumption Patterns in BC in a Global Context

British Columbia (BC), similar to the rest of Canada, has abundant water resources; however, its per capita water consumption is relatively high compared to other Canadian provinces. In 2022, Statistics Canada reported that the average person in BC used 286 liters of water per day, which is 63 liters more than the national average of 223 liters per person per day [10]. For comparison, the average household in Europe consumes approximately 144 liters of water per person per day [11]. Although various local socio-economic and environmental factors contribute to higher water consumption per capita in Canada, the comparatively lower cost of water is a significant factor. Canada, which holds approximately 20% of the world's freshwater reserves, is often perceived as having abundant water resources due to its high per capita freshwater availability [12]. In stark contrast, many European countries are confronting chronic water stress, prompting the adoption of conservation-oriented practices [13]. This demonstrates a growing policy emphasis in European countries on conservation and addresses the pressures brought about by droughts and water availability stress. On the other hand, water has been abundant and relatively underpriced in Canada. However, with increasing demand for water driven by rapid population growth and the depletion of freshwater supplies, the cost of water use is likely to rise in Canada, and water scarcity is expected to become a growing concern [14,15]. Figure 1 illustrates municipal water use across various buildings in Canada, with residential water use accounting for the largest share of the municipal water supply [16].

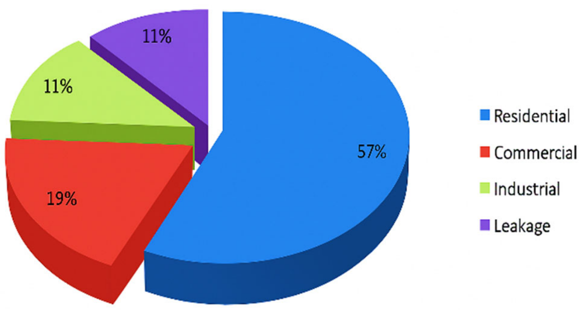

Figure 1. Municipal water consumption breakdown within sectors in Canada [16].

1.2. Waste Generation Patterns in BC in a Global Context

Solid waste refers to materials generated by human activities that are no longer needed [1]. It can be classified either by the source of generation, such as residential (single-family, multi-family, high-rise, and low-rise), commercial, institutional, or industrial, or by its composition, including organic matter, paper, glass, metal, plastic, and other forms. Canadian municipalities and some private organizations manage the collection, diversion and disposal of residential and non-residential solid waste.

In 2022, Canadians produced an average of 684 kg of municipal solid waste per person [4], significantly higher than the European Union's average of 513 kg [17] and lower than the U.S. average of 951 kg [18,19]. BC stood out with 479 kg per person [20], indicating effective waste reduction strategies adopted in the province.

Over the past two decades, Canada's waste diversion rates have shown measurable improvement, with residential diversion increasing from 24.8% in 2002 to 31.7% in 2022, largely driven by expanded recycling and composting initiatives [4]. In contrast, non-residential diversion rose only marginally, from 19.8% to 21.7%, highlighting persistent gaps in commercial and institutional waste management practices. In BC, the overall diversion rate (including both residential and non-residential) improved from 31.2% to 38.4% during the same period, demonstrating the province's strong focus on waste management. While residential practices show steady progress, the non-residential sector still has significant room for improvement, underscoring the need for enhanced management strategies in that sector. The comparisons indicate that there is considerable untapped potential to increase residential waste diversion in Canada by adopting policy, infrastructure, and behavioral change approaches similar to those implemented in the European Union.

In Canada, many provincial and municipal authorities establish waste reduction policies and programs and monitor waste management facilities and operations. As mentioned, BC has achieved a more substantial per capita reduction in the recent decade as compared to the Canadian national average. The province initiative is part of a broader effort to establish a circular economy, which emphasizes the sharing, reusing, repairing, and recycling of materials. However, the substantial variation in per capita waste generation across regions in Canada highlights significant opportunities for waste reduction through policy alignment, improved organics diversion, building-scale waste system design, and the adoption of circular economy principles.

1.3. Objectives and Scope of This Study

Despite extensive research on residential water and waste systems, such as water efficiency and waste diversion, there is a lack of integrated reviews connecting technical performance with governance, equity, cultural context, and environmental resilience in residential building sector. This paper is intended to address this gap. The paper utilizes a narrative and integrative review approach to synthesize policy documents, technical reports, and peer-reviewed literature, primarily published since 2010. This synthesis assesses current practices, emerging technologies and strategies, and regulatory frameworks related to water conservation, water reuse, waste diversion, and the circular economy. The focus is on key research questions that aim to maximize water efficiency and reuse in built environments. It explores the integration of rainwater harvesting, greywater treatment, on-site wastewater management, and the adoption of innovative water-saving fixtures and smart management technologies. The study investigates strategies to minimize solid waste generation, promote circularity in materials use, and integrate composting and recycling systems in residential and commercial buildings. It discusses the environmental resilience of water and waste systems under climate-related stresses and discusses equity, governance, and implementation challenges. The discussion covers the successful management strate-

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gies that encourage environmental accountability, flexibility, and community involvement, ending with important conclusions and prospective paths for inclusive and sustainable water and waste management in Canadian residential buildings.

2. Research Methodology

The review develops an integrated framework for evaluating residential water and waste systems, discussing technical efficiency, environmental performances, governance, and equity objectives. It involved identifying peer-reviewed journal articles through major academic databases such as Scopus, Web of Science, and Google Scholar, focusing primarily on papers published between 2010 and 2025 [21]. Each source was coded by system type (water or waste) and assessed across four domains: technical, environmental, governance, and equity (Table 1). Technical and environmental indicators included water demand reduction, leak detection, GHG emissions, and energy use; governance indicators captured regulatory feasibility, incentive structures, and municipal programs; equity indicators addressed affordability, service accessibility, and Indigenous participation. This structured coding enabled systematic comparison across sources, identification of trade-offs and synergies, and reproducible evaluation of emerging technologies, policies, and practices. The focus is on contemporary best practices, emerging technologies, and regulatory frameworks concerning water conservation, water reuse, waste diversion, and circular economy strategies. Throughout the paper, water and waste systems are considered as integral components of building design, with attention given to their combined roles in supporting environmental sustainability, system resilience, governance, and equity.

Table 1. Indicators of residential water and waste systems across technical, environmental, governance, and equity domains.

System	Technical Indicators	Environmental Indicators	Government Indicators	Equity Indicators
Water	Demand reduction, Leak detection	Energy use, Energy conservation, GHG emissions	Code, Pricing structure, Incentives	Affordability, Service access
Waste	Waste reduction, Diversion rate	Landfill reduction	Extended Producer Responsibility (EPR), Municipal programs	Participation, Community inclusion

Equity and governance were incorporated as key dimensions alongside technical and environmental performance. For each water and waste system component, evidence was assessed regarding regulatory feasibility and equity considerations such as affordability and Indigenous participation. These dimensions served as evaluative criteria throughout the framework.

To implement this integrated framework, indicators for each system component were reviewed across the technical, environmental, governance, and equity domains throughout this paper. The parameters to be discussed are summarized in Table 1.

After the Introduction and Research Methodology, Section 3 delves into water conservation strategies for residential buildings. This includes measures to conserve water, the reuse of greywater, rainwater harvesting, and the use of smart technologies. Section 4 discusses sustainable waste management, focusing on residential waste streams, methods for waste diversion, and policies oriented towards a circular economy. Section 5 explores the environmental resilience of water and waste systems under climate-related stress. Section 6 discusses equity, governance, and the social, cultural, and regulatory challenges influencing implementation. Section 7 discusses future opportunities and research gaps in sustainable water and waste systems. The concluding section synthesizes the key findings and outlines future directions for advancing integrated, resilient, and equitable water and waste management in Canadian residential buildings.

3. Water Conservation Strategies in Residential Buildings

Water conservation in residential buildings is achieved through a combination of technologies, conservation practices, and behavioral measures that aim to reduce overall water demand. Low-flow water fixtures such as faucets, showerheads, and dual-flush toilets significantly decrease daily consumption without compromising quality of life. High-efficiency appliances, including dishwashers and washing machines, further reduce water use while lowering energy demand [22]. One prominent study on water conservation was conducted by Price et al. [23]. A statistical regression analysis of a water utility rebate program examines its impact on residential water usage, revealing that the installation of low-flow toilets leads to the most significant reduction in water demand compared to other applications studied. While washing machines, dishwashers, and low-flow showerheads also contribute to notable decreases in water consumption, their impact is less pronounced than that of toilets. In contrast, certain applications like air conditioners and hot-water recirculation systems do not demonstrate a significant effect on overall water usage. By combining multiple water-saving measures, households can achieve substantial reductions in water demand.

Rainwater harvesting systems capture water for non-potable uses such as toilet flushing, irrigation, and outdoor cleaning, reducing reliance on municipal water supplies [24]. Greywater recycling with/without heat recovery system, which reuses lightly used water from sinks, showers, and laundry, provides an additional source for landscape irrigation or toilet flushing [25]. Smart irrigation systems also help minimize outdoor water consumption [26]. Beyond technology, household practices, such as leak detection, timely repairs, and water-conscious habits, play an equally important role in water conservation. Together, these strategies enhance water efficiency, reduce utility costs, contribute to long-term water security, and overall support buildings sustainability objectives.

3.1. Greywater Reuse and Onsite Treatment

In Canada, about 41% to 42% of total household water use is for toilets (about 24%), irrigation (about 15%), and outdoor cleaning (about 2–3%) [27]. Greywater generated from showers, bathroom sinks, and laundry accounts for approximately 50–80% of indoor residential wastewater volume, noting that this proportion refers only to wastewater entering the sewer system and excludes most outdoor water use [8]. Greywater reuse and on-site treatment are strategies for reducing potable water demand and promoting sustainability in residential buildings. Greywater from sinks, showers, bathtubs, and laundry can be collected and treated on-site through filtration, sedimentation, biological treatment, making it safe for non-potable uses such as toilet flushing, landscape irrigation, or outdoor cleaning (Figure 2) [27].

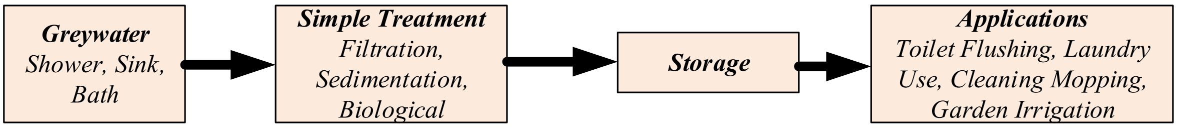

Figure 2. A simple line diagram of greywater treatment and reuse strategies.

On-site water treatment systems range from small-scale household units to larger multi-unit residential installations, allowing water to be reclaimed close to its source, reducing the need for transportation and municipal treatment [28]. This approach not only conserves freshwater resources but also decreases energy consumption associated with pumping and treating water in centralized systems. Certain municipal regulations and pilot programs are fostering the implementation of greywater systems in residential environments, underscoring their significance in sustainable water management, reducing utility expenses, and enhancing resilience to water scarcity [29,30]. However, a number of municipalities lack the requisite regulations and water quality standards necessary to ensure the safe and sustainable reuse of greywater [31].

3.2. Rainwater Harvesting and Reuse

Rainwater harvesting is increasingly recognized as a viable strategy for residential water conservation in Canada. Several regional districts in BC, including the Sunshine Coast and Nanaimo [32,33], offer rebate programs to encourage homeowners to install storage and filtration systems for capturing and reusing rainwater for garden irrigation or, in some cases, toilet flushing (Figure 3). The City of Vancouver is also updating its bylaws; beginning in 2025, new low-density residential developments will be required to implement on-site rainwater management measures [34], such as cisterns, permeable surfaces, or rain gardens, to reduce stormwater runoff and potable water demand.

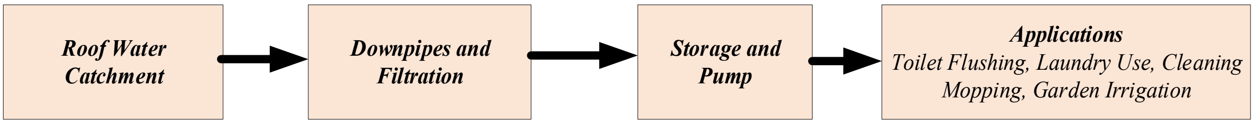

Figure 3. A simple illustration of rainwater harvesting system in buildings.

The adoption of rainwater harvesting faces several challenges, including restrictive plumbing codes, public health standards for water quality for reuse, and varying municipal approval processes for indoor non-potable water use [35]. In regions with colder climates, additional factors such as seasonal precipitation variations, risks of winter freezing, and difficulties in sizing storage systems further impact performance and acceptance. Therefore, rainwater harvesting should serve as a supplementary water source, integrated with demand-reduction measures and designed for local climate conditions. Conducting a local climate assessment is essential for adapting successful harvesting strategies to varied regions. In addition, water quality management, treatment needs, lifecycle costs, and maintenance duties also play significant roles in determining the feasibility of such systems. Nevertheless, existing government initiatives and demonstration projects indicate BC's gradual transition toward integrated water management strategies, which aim to alleviate the strain on municipal infrastructure while enhancing resilience against climate variability and water scarcity [36].

3.3. Smart Water Saving Technologies

A growing number of municipalities and regional districts in BC and other places are embracing smart technologies to enhance water conservation in buildings. Universal metering initiatives are underway in rural and First Nations communities in BC, such as in the Regional Districts of Okanagan-Similkameen and Central Kootenay, where advanced water meters and grant-funded installations are helping track usage, identify leaks, and improve resource management [37].

Vancouver is rolling out an Advanced Metering Infrastructure (AMI) pilot to enable more frequent and detailed consumption data [38]. At the same time, its Accelerated Metering program aims to equip all unmetered homes with usage-based billing by 2040. Cities like Surrey and Burnaby have launched rebate and pay-for-use programs to encourage residential adoption of metering, aligning billing with actual water use. Smart leak detection systems, such as those offered through the BC Non-Profit Housing Association's partnership with Water-Protec [39], add an additional layer of protection by automatically shutting off water flow when leaks are detected. Together, these IoT-enabled and data-driven interventions support conservation by making water usage visible, enabling behavioral change, reducing wastage, and allowing utilities to manage demand more efficiently.

Smart water technologies achieve maximum effectiveness when they are integrated into a cohesive system rather than used in isolation [40]. The most significant savings are realized when a combination of metering, analytics, automated control, and efficient fixtures is incorporated into a comprehensive building water management strategy. This integrated approach enhances overall efficiency and conservation efforts.

4. Solid Waste Management Systems

Solid waste management is a crucial element of sustainable buildings, which includes the processes of generation, collection, transportation, treatment, and disposal of waste materials to protect human health, conserve resources, and minimize environmental impact [41]. In Canada, residential building solid waste management is among the largest contributors to municipal waste. It includes everyday items, ranging from organic food scraps and yard trimmings to paper, plastics, glass, metals, textiles, and increasingly, electronic waste. Residential wastes account for nearly half of all municipal solid waste, with per capita generation varying by region due to differences in lifestyle, infrastructure, socio-economic conditions, and policies [4].

From a sustainability perspective, waste reduction and reuse at the source are prioritized above recycling and disposal, aligning with the waste hierarchy adopted in Canadian policy frameworks. Effective waste management begins with source separation at the generation, where residents sort materials into designated streams for recycling, composting, and landfill disposal (Table 2). This segregation is critical as it reduces contamination, improves recycling efficiency, and increases diversion rates. Building design, including waste storage space, bin accessibility, and collection infrastructure, plays a critical role in enabling effective source separation and resident participation. The effectiveness of source separation depends not only on infrastructure but also on resident awareness, convenience, and ongoing education [42].

Table 2. Summary of the waste management hierarchy and associated treatment pathways.

Stage	Waste Management Step	Description	Outcomes
1	Waste Generation (Baseline Condition)	Waste from residential activities	Mixed solid waste streams
2	Source Reduction and Reuse	Measures to avoid waste generation and extend product lifecycles	Reduced waste quantity and resource demand
3	Recycling (Material Recovery)	Separation and processing of recyclable materials	Recovery of paper, plastics, metals, glass
4	Composting (Biological Recovery)	Biological treatment of organic waste	Production of compost and soil amendments
5	Waste-to-Energy (Energy Recovery)	Thermal or biological conversion of residual waste	Energy recovery and volume reduction
6	Landfill Disposal (Last Resort)	Final disposal of non-recoverable waste	Long-term containment of residuals

4.1. Waste Diversion Strategies

Canadian municipalities manage residential waste primarily through curbside collection, green bin programs for organic materials, and blue box recycling systems. In contrast, high-rise and multi-family buildings often rely on centralized waste rooms, chutes, and compactors to support efficient collection and handling [43,44]. Beyond basic collection infrastructure, diversion strategies include composting programs that convert organic waste into soil amendments and recycling systems that recover materials such as plastics, metals, glass, and paper (Table 2). Despite these efforts, diversion performance continues to be constrained by several persistent challenges, including limited space for waste separation within buildings, contamination of recycling streams, and uneven levels of public awareness and participation.

Addressing these challenges requires a combination of behavioral and design-based interventions. Implementing education and incentive programs can enhance participation in recycling and waste management efforts. Additionally, designing buildings with user-friendly features, like clearly labeled sorting areas and easy access to diversion streams, can help minimize contamination and improper use of those systems. When integrated early in the design or retrofit of residential buildings, features such as dedicated waste storage areas, multi-stream chutes, and on-site composting systems can significantly reduce landfill disposal, conserve materials, and lower GHG emissions [45]. In this context, residential solid waste management plays a vital role in supporting both environmental performance and the long-term resilience of urban communities.

A Canadian example of a comprehensive approach is the Haldimand County Solid Waste Management Master Plan. This 10-year strategy emphasizes improvements to curbside collection, expansion of waste depots and special waste services, responsible management of closed landfill sites, and sustained public education and community engagement initiatives [46].

4.2. Waste Reduction and Circular Economy

As mentioned, sustainable practices focus on reducing waste at its source through strategies like minimizing packaging, promoting bulk purchasing, and replacing single-use items with durable alternatives. These preventive actions lessen landfill and conserve energy and resources.

The circular economy framework redefines waste as a valuable resource, emphasizing reuse, repurposing, and recycling instead of the traditional linear model (Table 3). Extended Producer Responsibility (EPR) is an environmental policy idea that requires producers to take responsibility for the management of their products throughout their entire life cycle, especially at the post-consumer stage [47]. The idea of EPR plays a vital role in fostering a circular economy by facilitating the closure of material loops. It encourages the practices of reuse and recycling, which in turn helps to minimize resource extraction and reduce waste generation. In BC, the focus is on zero-waste approaches, using the 5 R hierarchy (Reduce, Reuse, Recycle, Recovery, Residential Management) to prioritize reduction and reuse before recycling. To tackle the environmental impact of waste, the province is promoting the 5R initiative, which aims to reduce waste per person from 479 to 350 kg per year [48]. By integrating waste prevention at the generation level and circular economy principles, residential systems can advance beyond basic recycling and composting toward a model that conserves resources and fosters long-term sustainability.

Table 3. Conceptual comparison of linear, recycling, and circular economy models.

Concept	Process
Linear	Take → Make → Use → Waste
Recycling	Take → Make → Use → Recycle → (partial loop) → Waste
Circular	Take → Make → Use → Reuse/Repair/Recycle → back to Make

4.3. Policy, Innovation, and Community Engagement

Effective waste management depends not only on technical systems but also on governance structures and public engagement [49]. Municipal bylaws and national diversion targets provide the regulatory basis for waste reduction, while emerging technologies, such as smart collection systems, anaerobic digestion, and automated sorting, can improve operational efficiency and reduce contamination in recycling streams [50]. Public participation remains a critical factor. Education initiatives, incentive programs, and equitable access to services help ensure that residents in different housing types are able to participate meaningfully in diversion efforts. Ongoing performance monitoring, including tracking diversion rates and GHG reductions, supports transparency and allows municipalities to adjust programs over time.

A leading Canadian example is Vancouver's Zero Waste 2040 Strategic Plan, which sets a long-term goal of becoming a zero-waste city by 2040 [51]. The plan emphasizes reducing reliance on landfilling and incineration by applying the 5R Zero Waste Hierarchy, with priority placed on waste prevention, reuse, and recycling, and energy recovery reserved for residual materials. This framework aligns municipal waste management with broader circular economy objectives by promoting systems that retain materials in use for as long as possible. The current five-year implementation plan (2024–2028) outlines priority actions such as increasing residential participation in diversion programs, supporting sharing, reuse, and repair initiatives, reducing edible food waste, improving diversion of construction and demolition materials, and applying equity to waste management policies and programs.

5. Environmental Resilience of Water and Waste Systems

Environmental resilience in residential water and waste systems ensures continuous functionality during climate-related events, power outages, and infrastructure disruptions. By integrating strategies such as decentralized treatment, rainwater and greywater reuse, adaptive storage, smart monitoring, and a robust waste management infrastructure, these systems ensure continuous service while promoting sustainability and circular economy goals. The following sections will offer more insights into these challenges and opportunities.

5.1. Environmental Resilience of Water System

Environmental resilience in residential waste systems is critical for withstanding the increasing frequency and intensity of climate-related events such as extreme rainfall, droughts, and the possibility of power outages (Figure 4). Resilient building systems are designed to maintain water supply and waste management functionality even under these climate-related events and power outages. For the resilient water system as discussed in Section 3, strategies include rainwater harvesting, greywater reuse, on-site storage, and smart metering to optimize usage during scarcity.

Flood-resilient building designs incorporate permeable surfaces, green roofs, and detention basins to manage stormwater runoff and prevent property damage [52,53]. Wastewater systems are strengthened to handle surges in volume during heavy rainfall, while decentralized treatment units allow continued operation even when centralized infrastructure is compromised. Incorporating flexibility and adaptive capacity into these systems ensures that residential buildings can continue to provide safe water and manage wastewater effectively, protecting both human health and the climate change adaptability. Additionally, a backup power system, such as generators or solar-powered pumps, can maintain critical water and wastewater operations during power outages. Smart monitoring and automated controls allow for early detection of failures and adaptive responses, minimizing service interruptions. Together, these measures create residential buildings that are not only capable of withstanding environmental and infrastructural shocks but also contribute to long-term sustainability goals by conserving water, and promoting a circular approach to resources [54,55].

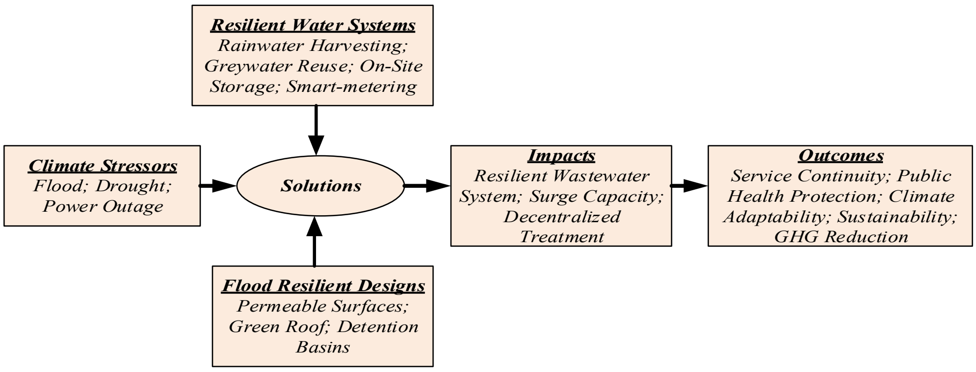

Figure 4. Conceptual framework illustrating environmental resilience in residential water systems under climate-related stressors.

5.2. Environmental Resilience of Waste System

Increasing climate instability, combined with infrastructure limitations and uneven waste practices across regions, has heightened the need for environmental resilience in waste systems [56–58]. In the context of high-rise and multi-family residential buildings, resilience is strongly influenced by how waste infrastructure is planned and operated. Well-designed storage rooms, flexible material separation arrangements, and effective compaction systems help manage waste accumulation and reduce the risk of system failure when collection schedules are disrupted by extreme weather or other service interruptions [1].

Resilience can also be improved through localized approaches to waste treatment. On-site or neighborhood-scale composting and organics diversion programs decrease reliance on centralized municipal services and provide additional capacity during periods of stress. At the same time, the adoption of smart monitoring technologies in several Canadian municipalities has introduced new opportunities for proactive system management. By generating real-time data on waste quantities, contamination levels, and related wastewater flows, these tools enable earlier detection of operational issues and support timely corrective actions.

Beyond maintaining operational performance, resilient waste management systems contribute directly to long-term environmental objectives. Increased diversion of organic materials and recyclables reduces landfill dependency and associated GHG emissions, while supporting resource recovery and circular economy principles. As climate change continues to intensify disturbance risks, resilient residential waste systems will become increasingly important in Canada, not only to ensure continuity of service but also to limit environmental impacts and strengthen sustainable material cycles [36]. Figure 5 provides a conceptual line diagram of resilient solid waste systems, illustrating how infrastructure design, decentralized organics handling, and digital monitoring interact to sustain performance under climate-related stressors.

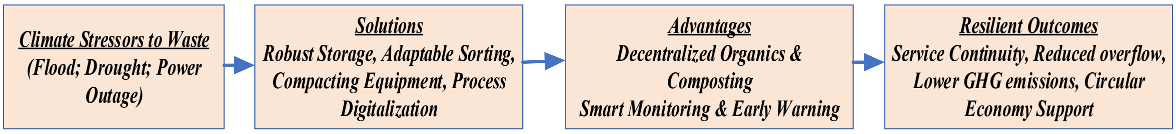

Figure 5. Line diagram illustrating key components of resilient solid waste management to minimize the impact of climate stressors.

6. Equity and Governance in Water and Waste Systems

Sustainable water and waste systems are influenced by technical performance as well as social, cultural, and governance factors. Key to building resilient and inclusive systems is equitable access, respect for Indigenous knowledge, and addressing economic and regulatory barriers.

6.1. Equity and Cultural Challenges

Equity and cultural aspects are crucial to the design of sustainable water and waste systems, as access to clean water and safe sanitation is a fundamental human right, and a prerequisite for a good quality of life [59–63]. Equitable access to water and waste systems addresses disparities in service delivery so that all communities, regardless of location or socioeconomic status, can benefit from reliable and affordable systems. In Canada, this is especially significant for Indigenous communities, where cultural practices and traditional knowledge emphasize respect for water as a sacred resource and guide sustainable management [36,64].

Many rural, remote, and northern communities continue to face infrastructure gaps, including long-term boil-water advisories and inadequate wastewater treatment, which highlight systemic inequities in clean water delivery and water resource management in some communities in Canada. Addressing these challenges requires not only technical solutions but also culturally informed approaches that include indigenous values and community engagement in planning and decision-making. Policy and governance play a crucial role in this process by ensuring inclusive consultation, providing adequate funding, and setting regulations that balance affordability with sustainability [65]. By integrating equity and cultural perspectives, water and waste systems can move beyond technical performance to become instruments of social justice, reconciliation, and community resilience.

Technically, greywater and rainwater harvesting systems must meet strict water-quality standards and be reliable, which can hinder widespread adoption [8,66–68]. Economically, high upfront costs and long payback periods of some of these solutions often discourage homeowners and developers, despite the clear long-term savings and benefits to health and the environment. Social factors, such as public awareness and acceptance, also play a crucial role in determining the effectiveness of solutions. Regulatory inconsistencies among provinces and municipalities create confusion regarding the rules that govern sustainable building systems. A coordinated approach is necessary to address challenges in water and waste systems, encompassing technical innovation, financial incentives, public education, and consistent regulations.

6.2. Policy, Standards, and Best Practices

Policy, standards, and best practices provide the framework for advancing sustainable water and waste systems in buildings, ensuring safety, consistency, and innovation. In Canada, building codes and provincial guidelines increasingly address water reuse, rainwater harvesting, and waste diversion, though implementation varies by provinces and municipalities [65]. For instance, some provinces allow rainwater collection for non-potable uses, while greywater reuse remains more tightly regulated due to health and safety concerns. International benchmarks such as LEED [66], WELL building standards [67], and the Living Building Challenge guide best practices by rewarding buildings that integrate water efficiency, waste reduction, and resource recovery into their design and operation. Municipalities can play a critical role by setting zoning requirements, offering incentives, supporting diversion programs, and creating public awareness, while developers influence outcomes through design choices, material selection, and infrastructure integration. Together, these policies and standards not only establish minimum requirements but also provide guidelines to municipalities that drive continuous improvement in sustainable building practices.

The main concept is that these systems are interconnected and shaped by essential factors [69]. Governance, encompassing policies and regulations, establishes the operational framework. Equity and cultural context are crucial, emphasizing that solutions must be fair and consider the social and cultural needs of the communities they serve. As the system moves forward, it faces barriers and challenges that must be overcome by increasing awareness and incentives. This leads to the need for future directions and innovation to develop new technologies and strategies. In an ideal system, all these elements work together to achieve a sustainable approach for managing water and waste.

7. Future Opportunities and Research Gaps in Sustainable Water and Waste Systems

As we look towards future innovations, it is increasingly clear that developing sustainable water and waste systems requires more than just technical solutions. Digital tools, such as sensor networks and data-driven analytics, are often praised for their potential to enhance system reliability and affordability. These devices can help with tasks like detecting leaks, forecasting demand, and providing early warnings of failures. However, the implementation of these technologies remains limited. Many of these solutions face challenges from cities and building operators due to fragmented data, a lack of in-house expertise, and uncertainty about long-term maintenance, Return on Investment (ROI), and cybersecurity. All these imply a gap that is less about inventing new technologies and more about awareness of how existing tools can be analyzed and implemented into everyday operational decision-making at various levels [70–74].

There are also some efforts to better integrate water, waste, and energy systems of buildings. Concepts such as wastewater heat recovery or decentralized treatment linked to building energy systems have been discussed for years and demonstrated at various scales. Yet these approaches are yet to be fully converted into large-scale viable solutions for a mass-scale implementation. Planning processes are often siloed, regulations do not align across sectors, and performance assessments tend to overlook a broader systems-thinking approach. More research is needed to examine how integrated systems perform over time, particularly under stress conditions, and how their environmental and economic value can be communicated in ways that support real-world adoption.

Social and cultural dimensions also remain underdeveloped in much of the existing literature. Many frameworks prioritize efficiency and emissions reduction but give less attention to questions of equity, governance, and local knowledge. Indigenous knowledge systems, which emphasize long-term stewardship and collective responsibility, are frequently acknowledged but rarely integrated in a substantive way. Addressing this gap will require research approaches that are more participatory and context-specific, allowing communities to shape not only outcomes but also how success is defined [75,76].

Additionally, progress in this field is closely tied to policy, financial support, and regulatory upgrades. Even well-established technologies can face significant barriers when upfront costs are high or regulatory requirements vary across jurisdictions. Financing

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mechanisms such as green loans, targeted subsidies, and public–private partnerships have shown promise, but their effectiveness depends heavily on local institutional capacity and policy alignment. Further research into these enabling conditions is essential if sustainable water and waste systems are to move from isolated examples to widespread practice.

8. Conclusions

The integration of sustainable water and waste systems is fundamental to advancing building resilience and environmental performance. Significant information has been published on the subject, and this overview paper is a modest attempt to highlight some of the key developments in terms of practices, technologies, and policy initiatives with a focus on BC and Canadian building infrastructure. Several recommendations have been drawn based on the information on the waste and water systems for future studies. It was concluded that further research is critical to making some emerging solutions and technologies viable, dependable, and affordable options. This review identifies several key insights for the future of residential water and waste management in Canada:

- Strategies such as greywater recycling and rainwater harvesting are effective at reducing potable water demand, though inconsistent municipal regulations and high upfront costs currently hinder their widespread adoption.
- Moving beyond traditional linear models toward a circular economy, prioritizing reduction, reuse, and repair, is essential for lowering GHG emissions and reclaiming value from waste.
- Maximum efficiency is achieved when smart technologies, such as advanced metering and leak detection, are integrated into comprehensive building management strategies rather than used in isolation.
- Technical performance must be balanced with social justice. Addressing infrastructure gaps in Indigenous and remote communities through culturally informed, inclusive governance is a prerequisite for a truly sustainable system.
- Realizing these goals requires breaking down planning silos, aligning cross-sector regulations, and fostering financial innovation to support large-scale, viable projects.

The transition to resilient and equitable water and waste management depends on a coordinated effort that combines technical innovation with a deep commitment to social and environmental responsibility.

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