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Enhancing water recycling adoption in South African residential properties: a multi-dimensional analysis for sustainable water management

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Abstract

This paper investigates the challenges and adoption rates of water recycling systems as a sustainable water management strategy within residential properties in South Africa. Employing a quantitative approach, the research incorporates a comprehensive literature review and household surveys to discern the micro-social, technical, and socio-economic motivations and challenges influencing adoption rates and homeowners' willingness to embrace water recycling systems. Through structural equation modeling (SEM), a causal model is developed, illuminating the intricate nexus between influential constructs, their sub-constructs, and the degree of water recycling system adoption in South African residential contexts. The SEM results reveal significant relationships between property characteristics, motivations, and challenges, and their combined impact on adoption rates. The study identifies a lack of space, unclear savings on water payments, and insufficient information/awareness as primary micro-level obstacles to implementing water recycling systems in residential properties. Furthermore, it demonstrates that enhancing the efficiency of water recycling systems could substantially mitigate the negative impacts of these challenges. The study underscores the pivotal role of public awareness campaigns and homeowner education in augmenting the utilization of recycled water within residential settings. Recommendations emphasize the necessity of equipping homeowners with fundamental environmental and technical knowledge pertaining to water recycling and advocate for government incentives to encourage the adoption of water recycling systems in residential properties. These findings offer valuable insights for crafting data-driven decision-making frameworks aimed at bolstering the capacity for analyzing and implementing novel water reuse strategies, tailored to the specific capabilities and resources of urban authorities and communities.

Article Highlights

- Water recycling adoption in South Africa faces challenges like limited space, unclear savings, and lack of awareness.
- Public awareness and government incentives are crucial for boosting water recycling in residential areas.
- Efficient water recycling systems can help overcome barriers and support sustainable water management.

Keywords Water recycling adoption · Challenges · Motivations · Multi-dimensional analysis · Residential properties · Sustainable water management

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1 Introduction

There is an increasing threat of urban water shortages in cities around the globe. The scarcity of water resources has become very critical, and among the most eminent risks to human wellbeing globally, in conjunction with socio-economic and ecological perils [1, 2]. Despite efforts of local and international bodies in setting up developmental programs that are meant to ameliorate water scarcity, the lack of access to potable water still persist [3]. Fanteso and Yessoufou [1] agree that although water is an abundant resource globally, its direct accessibility to address human and environmental needs is still lacking. This is partly attributed to the challenge of climate change, with exasperating issues of socio-economic development, emanating from exponential population growth and urbanisation [3, 4]. These are the major global megatrends that are speedily driving water scarcity universally alongside degradation of water resources [5].

Statistics have shown that more than half the world population already live in cities, and this population is predicted to increase to about 66% by 2050. This implies that more than two billion extra inhabitants will need water for drinking, food preparation and washing [6]. Consequently, as population and demand for freshwater resources rises, climate change and urbanisation with associated socio-economic advancement aggravates the impact of water scarcity universally, as supply remains constant, unfortunately [1, 4].

However, even when water cycle precipitates and returns water to earth, it is not always replaced in the same area with similar quantity and quality [7]. Hence, the freshwater supply differs over time, and its resources are unevenly distributed globally [8].

The challenges posed by climate change in South Africa have led to the loss of over 50% of the country's wetlands, with a substantial portion of the remaining wetlands in a deteriorating condition [9]. As a consequence of these climatic shifts, South Africa now ranks as the 30th driest country globally, experiencing markedly reduced rainfall patterns, receiving less than 50% of the global average [10]. Despite the critical role of local government in water redistribution, South African municipalities grapple with financial and infrastructural inadequacies, perpetuating inequality in water access [11]. Additionally, Mpofu et al. [10] highlight the strain on South Africa's water operations due to aging infrastructure, exacerbated by significant underinvestment and delays in maintenance and renewal efforts. Viljoen and Van der Walt [9] further underscore the challenges stemming from a lack of skilled personnel to undertake necessary maintenance projects, resulting in difficulties in cost recovery.

However, as South Africa's water supply dwindles due to these multifaceted challenges and the constrained access to natural water sources, the demand for water continues to surge, driven by unplanned population growth. Projections suggest that by 2030, water supply in South Africa will likely fall short of demand, rendering access to clean water one of the most pressing challenges in the upcoming decades [4].

Buildings contribute substantially to global freshwater usage, accounting for at least 30% of consumption [6]. As occupants of these buildings, individuals play a significant role in freshwater consumption. Thus, the implementation of sustainable water management practices becomes imperative to ensure reliable water supplies for current and future generations [12]. Within this framework, water recycling in residential properties emerges as a cornerstone of sustainable water management in urban areas.

Moreover, emerging evidence indicates that vulnerability to water scarcity extends beyond climatic factors and encompasses non-climatic drivers such as income, age, and gender [3]. Consequently, addressing water scarcity demands a multifaceted approach that goes beyond traditional supply, management, and technological considerations. It must also encompass social capital, institutional dynamics, livelihoods, and well-being dimensions [3, 13]. Thus, comprehensive responses to water scarcity challenges should integrate these broader socio-economic and institutional perspectives into planning and management frameworks.

The understanding of how communities and households indulge in water management and recycling practices can provide the necessary bedrock for informed initiatives required for behavioural change that can leverage on building new policies and investments [14, 15]. However, limited knowledge exists that creates awareness about the drivers of adopting water recycling systems in residential properties in relation to household characteristics, motivations, and challenges. Currently, no research exists that evaluates the causality and impact of these drivers on the extent of water recycling systems in residential properties in South Africa especially and Africa in general. Furthermore, no empirical evidence exists that indicates that houses characteristics and residents' awareness influence the extent of water recycling systems in residential properties. Consequently, planners, building designers and policymakers are confronted with several challenges as a result of this knowledge gap, in exploring opportunities and enhancing their knowledge on the extent of water recycling in residential properties. Hence, this groundbreaking study pioneers an investigation into the impact of house characteristics, micro-motivations, and challenges on the adoption and extent of use of water recycling systems within South African middle-income residential properties, employing a comprehensive causal model. The aim of the study is to provide a broader the micro-social, economic, and technical comprehension of water recycling adoption, in middle-income households, using an evidence-based approach, that enables water professionals to target engagement tools that promote water recycling in residential properties.

2 Literature review

Water scarcity remains one of the most challenging issues in contemporary times. The demand for urban water is forecasted to surpass supply by 2030, making the supply of potable water one of the most significant challenges for cities in the near future [4]. It has been estimated that about 2.7 billion people will face water scarcity by 2050 [16]. Many developing countries in Sub-Saharan Africa, Asia, and Latin America are confronted with either physical or economic water scarcity, reflected in high to extremely high-stress zones [4]. Real scarcity occurs when there is inadequate water to match the need for it, whereas economic scarcity happens when there is water poverty or a lack of investment in water infrastructure. According to the UN World Water Assessment Programme [16], one-fifth of the global population, or around 1.2 billion people, are currently situated in physically water-scarce areas, while 1.6 billion people live in areas of economic scarcity. Global water scarcity predictions indicate very disturbing results, speculating that water scarcity could displace 700 million people by 2030, exacerbated by climate change and water pollution [3, 4, 6].

2.1 Water scarcity in South Africa

South Africa is one of the most water-scarce countries globally, ranking among the top 30 driest nations. The country receives approximately 40% less rainfall than the global annual average, with an average annual rainfall of less than 500 mm, compared to the global average of around 850 mm [17].

South Africa's per capita water availability is estimated to be between 800 and 900 cubic meters per person per year, classifying it as a water-stressed country [18]. In global terms, water stress occurs when per capita water availability falls below 1700 cubic meters per year, and water scarcity is defined as availability below 1000 cubic meters per year [19]. Moreover, South Africa's water resources are unevenly distributed, with some regions experiencing significantly higher levels of water scarcity, exacerbating the challenges of managing the nation's limited water supplies.

In South Africa, a 17% demand gap (about 2.7 billion m^3) is forecasted by 2030, potentially increasing to 3.8 billion m^3 when climate change impacts are considered [20]. South Africa currently receives less than 50% of the global rainfall average, with climate projections indicating a reduction in precipitation in the region soon [4]. Total wet day precipitation is forecasted to reduce by about 15–45%, with up to a 30% reduction in some areas around the west coast [21]. Urban water demand in South Africa accounts for about 3.5 billion m^3 of the total water demand, with agricultural demand at 8.4 billion m^3 and industrial demand at 1.5 million m^3 [20]. However, the pools that provide water to Cape Town, Johannesburg, and Durban are speculated to face intense shortages as water demand rises. It is predicted that by 2030, supply–demand gaps of up to 31% and 39% will be experienced by the Upper Vaal and Olifants water management areas, respectively, which supply Johannesburg [4]. Similarly, there will be a 28% demand gap in the Western Cape Water Supply system, including the Berg water management area, which supplies water to Cape Town [4, 20].

2.2 Strategies for addressing water scarcity

To ensure water security, the water scarcity challenge can be resolved in different pragmatic forms that balance water supply and demand. These include allocating water for various uses, policy reforms and interventions, water management reforms, and proper investments that ensure sustainability in water use. The OECD [22] identifies three broad strategies to address challenges associated with water scarcity:

1. Investment in Infrastructure: Refurbishing old water systems to reduce water loss and broadly expand water supply for all purposes is crucial. Despite being a significant expense, new water supply projects are necessary, especially in the global south, to meet the forecasted exponential growth in water demand. This requires cautious, choice-driven, and economically structured development of new water provisions through the expansion of capacities for water supply. This aligns with SDG 6 (Clean Water and Sanitation), particularly Target 6.4, which aims to substantially increase

water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity.

2. Water Conservation and Efficiency: Enhanced efficiency in existing water use can be achieved through water management and incentive policy reformation. This includes water pricing policy, water reuse or recycling policy, adding water meters to reduce consumer water usage, and formalizing the use of household water-efficient appliances. Although water is termed a scarce resource, humans can devise means to use it more efficiently. These actions are directly related to SDG 12 (Responsible Consumption and Production), specifically Target 12.2, which focuses on achieving the sustainable management and efficient use of natural resources, and SDG 6 (Clean Water and Sanitation), particularly Target 6.4 on increasing water-use efficiency.
3. Non-Conventional Water Resources: Employing non-conventional water resources for water supply, such as rainwater harvesting and greywater recycling and reuse, is essential. A high percentage of consumed water is untreated, and the copiously available yearly precipitation is not utilized effectively. This approach not only addresses immediate water scarcity but also integrates with SDG 6 (Clean Water and Sanitation), specifically Target 6.3, which aims to improve water quality by reducing pollution, eliminating dumping, minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.

2.3 Adoption of water recycling systems

Decentralized water recycling systems, particularly in residential properties in developing countries facing significant water scarcity, offer a sustainable solution to provide safe, acceptable, and affordable water. Key factors influencing the adoption of these systems include technology availability, location, and expansion potential. Increasingly, governments and water management bodies are recognizing the importance of addressing water security challenges through the promotion and installation of water recycling systems, such as rainwater harvesting and greywater treatment [23].

These systems play a critical role in addressing water security challenges by reducing dependency on traditional water sources and promoting efficient water use [2]. Key factors influencing the adoption of these systems include the availability of technology, the location of the properties, and the potential for expansion and scalability [13, 24].

Globally, water recycling has become a vital component of sustainable water management strategies. For instance, Singapore's innovative approach to water recycling, known as "NEWater," serves as a benchmark for effective water reuse [25]. Singapore converts its sewage into potable drinking water through advanced treatment processes, including microfiltration, reverse osmosis, and ultraviolet disinfection. This process ensures that the reclaimed water meets or exceeds the World Health Organization's drinking water standards [26]. Singapore's success in integrating water recycling into its national water strategy highlights the potential for similar approaches in other regions facing water scarcity.

In Israel, another global leader in water recycling, over 80% of wastewater is treated and reused for agricultural purposes, making it the highest rate of water reuse in the world [27]. The country's comprehensive water management policies, coupled with advanced recycling technologies, have enabled it to transform wastewater into a valuable resource for irrigation, contributing significantly to its agricultural productivity and water sustainability.

In Australia, particularly in arid regions, water recycling has been incorporated into urban planning and development. Techniques such as stormwater harvesting and the use of treated wastewater for non-potable purposes have been widely adopted [28]. The Australian government's investment in public awareness campaigns and incentives has played a crucial role in increasing the acceptance and implementation of water recycling practices [29].

In contrast, while residential piped water distribution reaches 95% in urban areas of the global north, only 42% of urban regions in the global south have similar access [30]. This disparity underscores the need for alternative solutions like water recycling systems in the global south generally and South Africa specifically, where traditional infrastructure may be inadequate or unsustainable [10].

In South Africa, water recycling systems offer a promising solution to the country's ongoing water scarcity challenges. Although the government has allocated R115 billion for water and sanitation infrastructure until 2024 [31], specific figures for the current budget dedicated to water recycling infrastructure are not readily available. Given the extensive demands on water and sanitation infrastructure, it appears that the budget may be insufficient to fully support the development of the necessary water recycling systems to ensure a sustainable water supply, particularly in regions most affected by water scarcity [31]. This underscores the need to explore decentralized micro water recycling systems as a viable alternative. However, the adoption of these systems is linked to various socio-economic factors and the typology and condition of residential buildings. The lack of infrastructure, high costs, and limited public awareness are significant barriers. Understanding these factors, alongside property characteristics, motivations, and challenges, is crucial for fostering greater acceptance and adoption of water recycling systems in residential properties.

2.3.1 Characteristics of residential property

The characteristics of residential properties play a pivotal role in the adoption and implementation of water recycling systems [32, 33]. These characteristics determine the technical and logistical challenges that property owners might face. Understanding these characteristics is particularly important in the global south, where diverse housing conditions and infrastructural disparities exist [34, 35]. Tailoring water recycling solutions to the specific attributes of residential properties can significantly enhance adoption rates and contribute to more sustainable water management practices.

The type of house significantly influences the feasibility of installing water recycling systems [36]. Detached houses, for instance, offer more space and flexibility for such installations compared to multi-unit buildings. This distinction is crucial in the global south, where housing diversity is wide. As demonstrated by Lee and Jepson [37], properly designed systems tailored to different house types can significantly enhance adoption rates. Older properties may face challenges in retrofitting water recycling systems due to outdated plumbing and structural constraints. However, these properties often have larger plots, which can be advantageous [32]. Understanding the age-related infrastructure limitations helps in designing compatible systems that promote water recycling.

Roof types play a pivotal role in rainwater harvesting, a common water recycling method [38]. Pitched roofs with suitable materials are more effective for collecting rainwater [39]. In regions like the global south, where rainfall can be sporadic yet intense, optimizing roof design for water collection can significantly improve system efficiency [40]. Space availability is another critical factor in the adoption of water recycling systems. Properties with ample outdoor areas can accommodate tanks and treatment facilities more easily. Ensuring adequate space in residential planning can enhance the feasibility of these systems in densely populated areas [32]. Gardens provide an ideal area for utilizing recycled water, particularly for irrigation. Properties with gardens can directly benefit from water recycling, reducing dependence on potable water for landscaping [37].

The existing water supply system impacts the integration of water recycling technologies. Properties with modern plumbing can more easily incorporate dual systems for potable and non-potable water [41]. Enhancing existing supply systems in developing countries can facilitate smoother adoption of water recycling practices. On the other hand, an efficient wastewater system is essential for the effective operation of greywater recycling. Properties equipped with separate greywater and blackwater systems simplify the recycling process [42]. In the global south, upgrading wastewater infrastructure can significantly promote the use of recycled water. The cost of water also influences the willingness to invest in recycling systems [43]. In regions where water is expensive, there is a stronger incentive to adopt technologies that reduce consumption. Policies that reflect the true cost of water can motivate property owners to embrace recycling systems [13, 33].

Based on the foregoing, it is evident that the characteristics of property attributes influence the adoption of water recycling within residential buildings, particularly housing. Hence, the following hypothesis is proposed:

H1: There is a significant association between residential property characteristics and the level of adoption of water recycling systems.

2.3.2 Motivations on adoption of water recycling systems

Motivations for adopting water recycling systems are diverse and can significantly influence the willingness of property owners to implement these technologies [24, 32]. These factors drive adoption by highlighting benefits and addressing the specific needs and values of the community [43, 44]. In regions like the global south, where water scarcity is a pressing issue, the financial savings and environmental benefits of water recycling are compelling motivators [3]. Additionally, cultural and religious practices that emphasize sustainability and conservation can further encourage the adoption of these systems [14]. Understanding and leveraging these motivations is crucial for designing effective policies and campaigns to promote water recycling.

Government and private incentives play a crucial role in encouraging the adoption of water recycling systems. Subsidies, tax breaks, and grants can offset the initial costs of installation [45]. Effective government policies in the global south can promote sustainable water use practices among property owners. Reducing water bills is also a strong motivation for adopting recycling systems. By using recycled water for non-potable purposes, households can significantly lower their water expenses [13]. In the global south, where economic constraints are prevalent, this financial benefit can drive widespread adoption.

Environmental protection is a key motivation for adopting water recycling systems. By reducing reliance on freshwater sources, these systems help conserve natural resources and reduce pollution [32]. In the global south, where environmental degradation is a major concern, this motivation can significantly boost adoption rates [15, 41]. Water scarcity and drought conditions are also powerful motivators for adopting water recycling systems. In regions frequently affected by water shortages, such as many parts of the global south, the necessity of alternative water sources becomes evident. These conditions can accelerate the adoption of recycling technologies [46].

Cultural practices influence the acceptance and use of water recycling systems. Societies with traditions of water conservation and reuse are more likely to embrace these technologies. Understanding and integrating cultural practices can enhance the acceptance of water recycling systems in various communities [14, 15]. Furthermore, religious beliefs and practices can influence the adoption of water recycling systems [34, 47]. In some cultures, religious guidelines promote the sustainable use of natural resources, including water. Leveraging religious teachings to advocate for water recycling can be an effective strategy in promoting these systems [13].

General awareness of the need for water conservation can drive the adoption of recycling systems. Educating communities about the benefits of conserving water through recycling can foster a culture of sustainable water use [13]. In the global south, conservation efforts are crucial for long-term water security.

Based on the foregoing, it is evident that various motivations such as financial, environmental, cultural, and religious factors influence the adoption of water recycling systems within residential properties. Hence, the following hypothesis is proposed:

H2: There is a significant association between motivations for adopting water recycling systems and the level of adoption of water recycling systems.

In addition to the direct association between motivations for adopting water recycling systems and the level of adoption (H2), according to literature reviewed above there is a potential indirect association mediated by the characteristics of residential properties. This relationship suggests that property characteristics could influence the effectiveness of motivational factors in promoting water recycling adoption. The hypothesis formulated to explore this indirect association is as follows:

H3: There is a significant association between residential property characteristics, motivations for adopting water recycling systems, and the level of adoption of water recycling systems.

2.3.3 Challenges on adoption of water recycling systems

Despite the various motivations driving the adoption of water recycling systems, several significant challenges can hinder their implementation in residential properties [32]. These challenges are particularly pronounced in the global south, where economic constraints and infrastructural limitations are more prevalent [4]. Addressing these challenges requires a multifaceted approach, including technological innovation to reduce costs and energy consumption, educational campaigns to increase awareness, and policy interventions to provide financial incentives [41]. Overcoming these barriers is essential to facilitate the widespread adoption of water recycling systems and achieve sustainable water management in residential areas.

A major challenge is the lack of awareness about the benefits and feasibility of water recycling systems [48]. Education and outreach programs are crucial to inform property owners about how these systems work and their advantages. Increasing awareness can drive higher adoption rates, particularly in the global south. Another significant barrier is the perceived lack of clear savings from water recycling systems. If the financial benefits are not immediately apparent, property owners may be reluctant to invest [37]. Demonstrating long-term cost savings through pilot projects and case studies can help overcome this barrier.

High capital and operational costs are also significant barriers to the adoption of water recycling systems. The initial investment required for installation and the ongoing maintenance expenses can be prohibitive [13]. Reducing these costs through technological innovation and subsidies can enhance adoption rates in the global south. Additionally, the availability and suitability of water recycling technologies in local markets is critical. The global south often lags behind in accessing the latest innovative technologies compared to the global north [41]. Ensuring that suitable technologies are accessible and affordable is crucial [49].

The energy-intensive nature of some water recycling systems can be a drawback. High energy consumption increases operational costs and reduces the environmental benefits. Developing energy-efficient technologies is essential to make water recycling more sustainable and attractive [41, 44]. Limited space in residential properties can also restrict the installation of water recycling systems. Urban areas, in particular, face this challenge. Designing compact and efficient systems that can fit into smaller spaces can help overcome this barrier and promote wider adoption [32].

Cultural resistance to using recycled water can be another significant barrier. In some societies, there may be stigmas or misconceptions about the safety and cleanliness of recycled water. Addressing cultural concerns through education and community engagement is vital for increasing acceptance [14, 49]. Similarly, religious beliefs can also impede the adoption of water recycling systems if they conflict with the use of recycled water [49]. Engaging religious leaders and communities in discussions about the benefits and safety of recycled water can help align religious practices with sustainable water use [50].

From the foregoing, various challenges impede the adoption of water recycling systems within residential properties. This study seeks to examine the negatively mediating effect of these challenges on the association between the level of adoption of water recycling systems and identified challenges and barriers. To achieve this, the following hypothesis has been articulated:

H4: There is a significant association between challenges for adopting water recycling systems and the level of adoption of water recycling systems.

Similar to motivations, there is a potential indirect association mediated by the characteristics of residential properties between challenges for adopting water recycling systems and the level of adoption. This relationship suggests that property characteristics could negatively influence the adoption of water recycling systems. The hypothesis formulated to explore this indirect association is as follows:

H5: There is a significant relationship between residential property characteristics, challenges for adopting water recycling systems, and the level of adoption of water recycling systems.

Addressing water scarcity requires a multifaceted approach that balances supply and demand through infrastructure investment, conservation, efficiency, and the use of non-conventional water resources. Promoting awareness and understanding socio-economic and cultural factors are crucial for the successful adoption of water recycling systems in residential properties. This study proposes a causality model based on hypothesized relationships to analyze these dimensions and formulate a decision-making framework for effective water reuse implementation.

3 Causality model constructs and sub-constructs

Through an extensive review of the literature, with a particular emphasis on the context of the global south and South Africa, the study identified 23 sub-constructs under three main constructs, as summarized in Table 1.

The localized sub-constructs and formulated research hypotheses extracted from the literature were then utilized to develop a theoretical framework. This framework details the causality between the three constructs (characteristics of residential property, motivations, challenges) and their sub-constructs in relation to the level of adoption of water recycling in South African residential properties, as illustrated in Fig. 1.

The five hypotheses posit that motivations and challenges for adoption, as independent constructs, directly influence the level of adoption of water recycling systems (H2 & H4). Additionally, the characteristics of residential property have a direct association with the level of adoption (H1). Moreover, these property characteristics also mediate the relationship between motivations and challenges and the level of adoption (H3 & H5), acting as a mediating construct.

4 Research method

The research utilised a quantitative approach, classified under positivism philosophical research that supports empirical studies to examine the association and causality between house characteristics, motivation, challenges, and extent of water recycling systems use in South African residential properties. A survey was conducted to scrutinise the challenges and extent of water recycling systems use in residential properties in South Africa.

Data collection was conducted across a spectrum of household incomes in three major South African metropolises: Johannesburg, Cape Town, and Durban. Electronic structured questionnaires were distributed to 3000 residential property owners in these areas through various channels, including local neighborhood communities and social media platforms. There were 2,010 valid responses collected (69% response rate) and used for further data analysis. The questionnaire consisted of five sections: general residential household information, residential buildings

Table 1 Constructs and variables of the study

Constructs	Sub-constructs	Source
Characteristics of residential property	Type of house	[34, 36, 38]
	Age of property	[34, 36, 39]
	Type of roof	[32, 34, 38, 39]
	Water supply system in the property	[34, 37, 39, 41]
	Wastewater system in the property	[34, 37, 39, 41]
	Availability of space for installing water recycling system	[32, 34, 36, 37]
	Availability of garden in the property	[34, 36, 37, 40]
	Affordability of water	[13, 34, 37, 40]
Motivations on adoption of water recycling system	Reduction of water bills	[13, 32, 34, 37, 40, 43]
	Government incentives	[13, 32, 34, 37, 43]
	Protect environment	[3, 32, 34, 40, 43, 46]
	Cultural practice	[3, 14, 32, 34, 37, 43, 46]
	Shortage of water/ drought	[3, 4, 32, 34, 37, 43, 46]
	Conservation of water	[4, 32, 34, 40, 43, 46]
	Religious practice	[3, 32, 34, 37, 43, 50]
Challenges on adoption of water recycling system	Capital & operational costs	[13, 32, 34, 37, 40, 41, 43]
	No clear saving	[13, 32, 34, 37, 40, 43]
	Lack of awareness	[3, 32, 34, 37, 41–43, 48]
	Unavailability of technology	[32, 34, 41, 43, 45]
	Not accepted by cultural	[3, 14, 32, 34, 37, 42, 43, 48]
	Not accepted by religion	[3, 14, 32, 34, 43, 48, 50]
	Energy-intensive	[32, 34, 37, 41, 43, 45]
	Lack of space at the property	[32, 34, 37, 38, 42, 43]

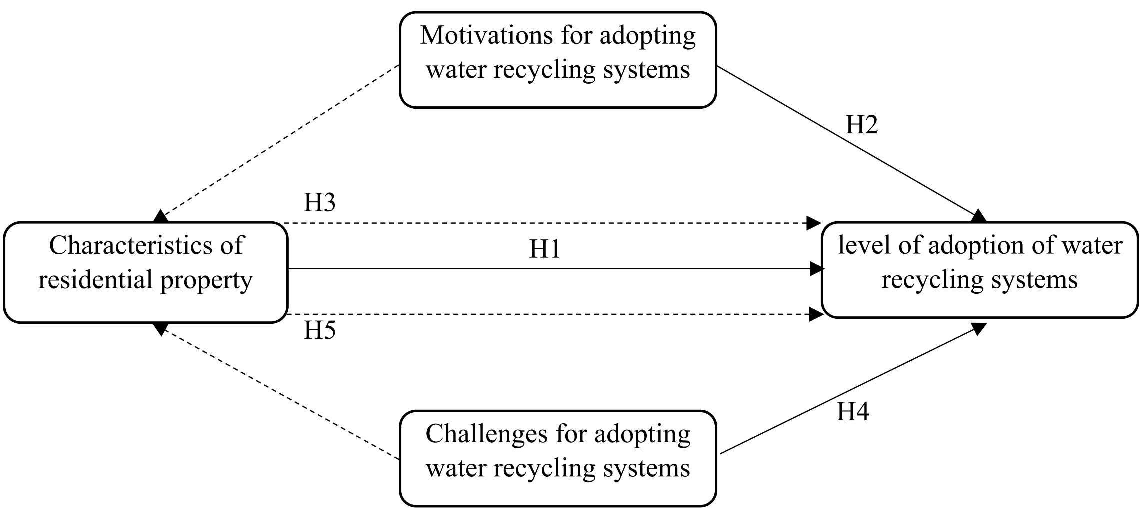


Fig. 1 Causality model of water recycling system in residential properties

characteristics, water recycling systems use, motivations and challenges in adopting water recycling systems in residential properties. Descriptive and inferential statistics were used to analyse the collected data to identify the influences on utilising water recycling systems in South African residential properties. Structural Equation Modelling (SEM) was used as a robust statistical method to validate the association between the houses' characteristics, motivations, and challenges in adopting water recycling systems in residential properties.

The SEM analysis in this study involved five key steps of:

- Model specification outlines the hypothesized relationships among the constructs.
- Model identification evaluates the overall model fit using fit indices for testing individual path coefficients.
- Model evaluation involves assessing the model's performance and calculating quantitative indices to determine the overall appropriateness of fit.
- Modification involves adjusting the model to enhance its fitness.
- Validation improves the reliability and stability of the causality model for water recycling systems in residential properties.

5 Results and discussions

5.1 Profile of property owners

The demographic information of 2,010 property owners participated in this study are shown in Fig. 2.

As shown in Fig. 2, most of the residential property owners are young professionals between the age of 30–49 (54%) that work full/part-time (78%) and fall under middle income (77%).

5.2 Characteristics of property

The characteristics of 2010 residential properties are summarized in Fig. 3. Of these, 88% are owned by households, while only 12% are owned by the government, a factor that enhances the adoption of water recycling systems in properties, as demonstrated by the study conducted by Radcliffe and Page [28]. As shown in Fig. 3 detach (35%) and apartment (27%) are more common type of houses, and pitched roof is more popular than flat roof in South Africa. The result shown that 76% of properties are built more than ten years ago.

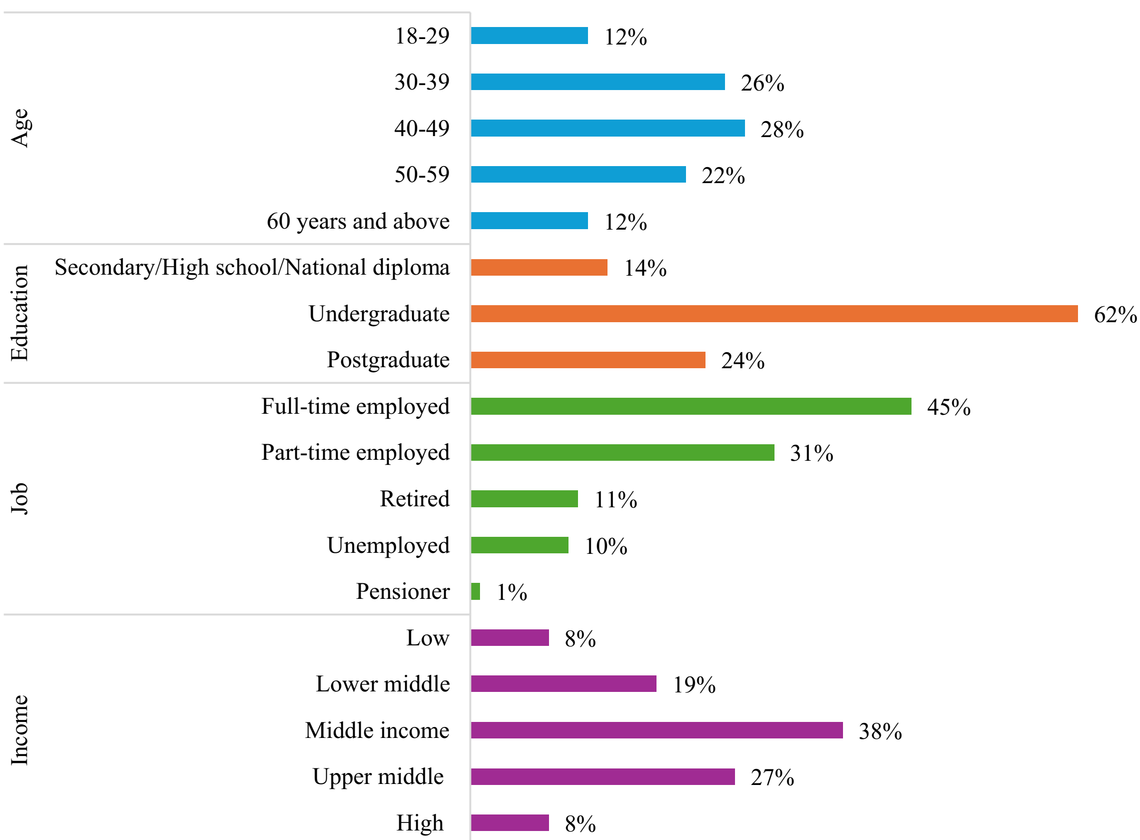


Fig. 2 Profile of property owners

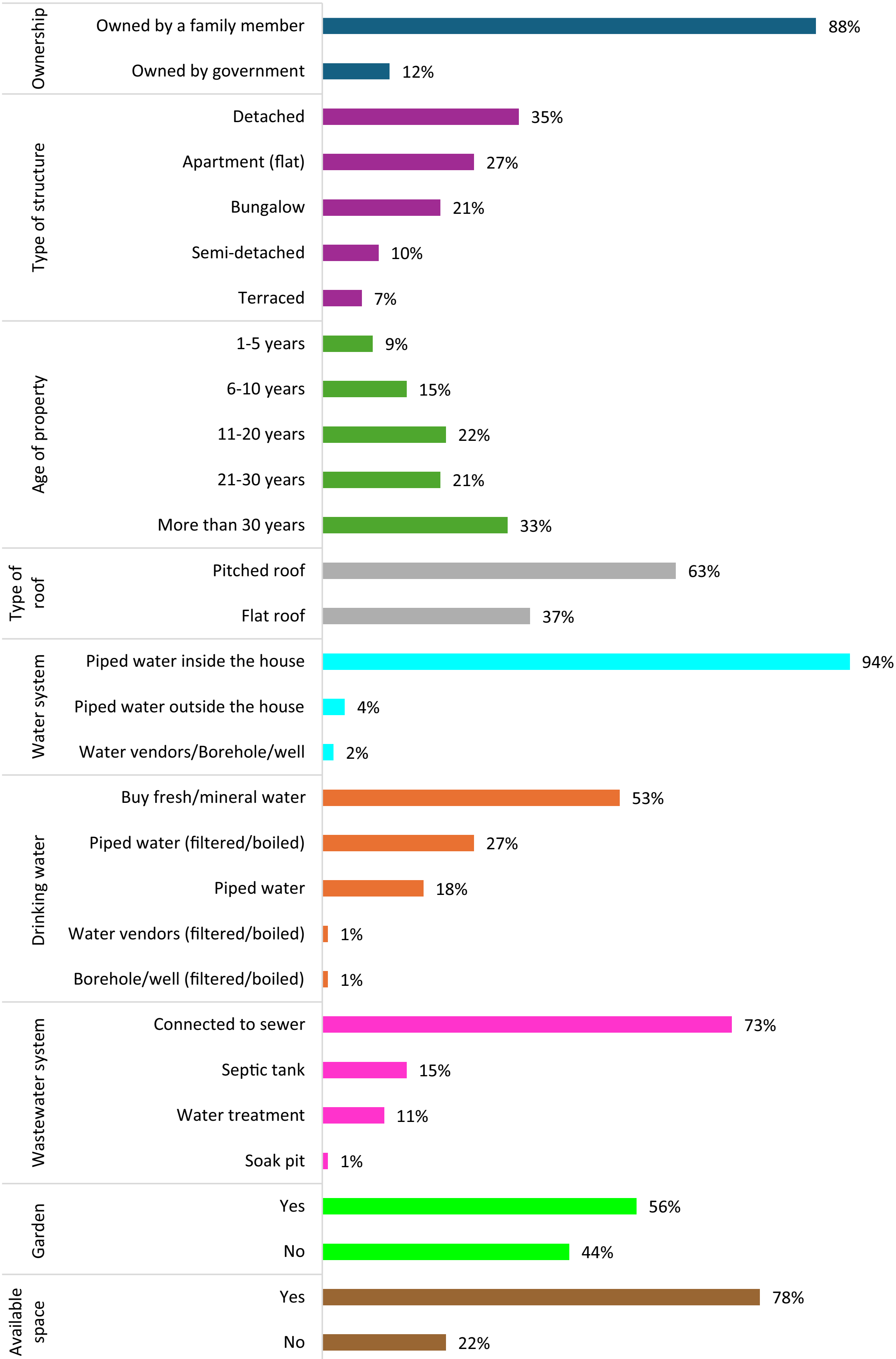


Fig. 3 Characteristics of residential properties

Although 94% of residential properties are connected to municipal water pipes, only 18% of households actually drink water directly from these pipes, with 53% opting to purchase fresh or mineral water. These figures underscore the pervasive issue of water quality in South Africa, a concern highlighted in previous studies such as Verlicchi and Grillini [51]. Similarly, the majority of residential properties (73%) are connected to municipal sewer systems. Furthermore, as depicted in Fig. 3, 56% of properties boast gardens, incentivizing property owners to utilize recycled water for garden irrigation, as demonstrated by the study conducted by Alim et al., [36] and Fielding et al. [48]. Over 78% of houses have sufficient space for installing water recycling systems, thereby enhancing the potential for utilizing such systems in properties, another key motivation supported by the findings of Chen et al., [32] and Stec and Słyś, [13] in residential properties.

5.3 Water recycling information

The analysis of collected data reveals that while water is affordable for 91% of households, nearly all surveyed households demonstrate awareness of the importance of water recycling (97%), with 89% expressing willingness to reuse recycled water for non-potable uses within their homes, as illustrated in Fig. 4. The widespread agreement on using recycled water may stem from households' heightened awareness of the critical role of water recycling, particularly in response to severe drought situations experienced in past years, such as the Day Zero crisis in South Africa [52].

As depicted in Fig. 5, a significant number of residential properties have adopted rainwater harvesting (89%) and greywater systems (58%) as the most common water recycling methods. This high level of adoption of water recycling systems in South Africa may primarily be attributed to severe drought situations experienced in past years [52]. Furthermore, this finding supports the positive correlation between the extent of utilization of water recycling systems as an alternative water source and regions facing high water stress and crises, as proposed by Zavala et al. [53].

A closer examination of the data revealed that the utilization of rainwater harvesting systems (89%) far exceeds the implementation of greywater recycling systems (58%). This difference could be attributed to the higher capital costs and operational expenses associated with greywater systems, or the lack of efficient and affordable greywater technologies available in the local market [41, 54].

The analysis of water recycling systems reveals that low-tech solutions, such as storage tanks for harvesting rainwater and natural-based filtration for greywater, are more popular. This preference can be attributed to the lower capital and operational costs associated with these low-tech systems compared to their high-tech counterparts, as demonstrated by Maniam et al., [49] and Kuok and Chiu [55] in their study.

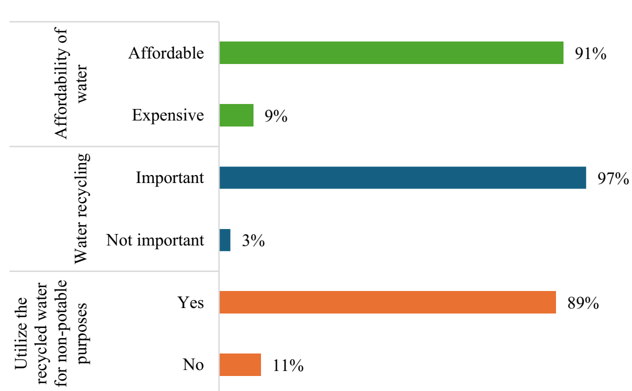
Similarly, recycled water from both rainwater harvesting and greywater systems is primarily used for non-potable purposes, such as flushing toilets and watering gardens. These findings are supported by the study conducted by Moghayedi et al. [34], which identifies garden watering and toilet flushing as the predominant uses of recycled water in urban areas.

5.4 Challenges and motivations on utilising water recycling systems

Key challenges and motivations for adopting water recycling systems in South African residential properties are identified, as depicted in Figs. 6 and 7.

The analysis of challenges in implementing water recycling systems reveals that the most significant obstacles in South African residential properties are capital and operational costs (35%), limited space (21%), unavailability of

Fig. 4 General households' water recycling information



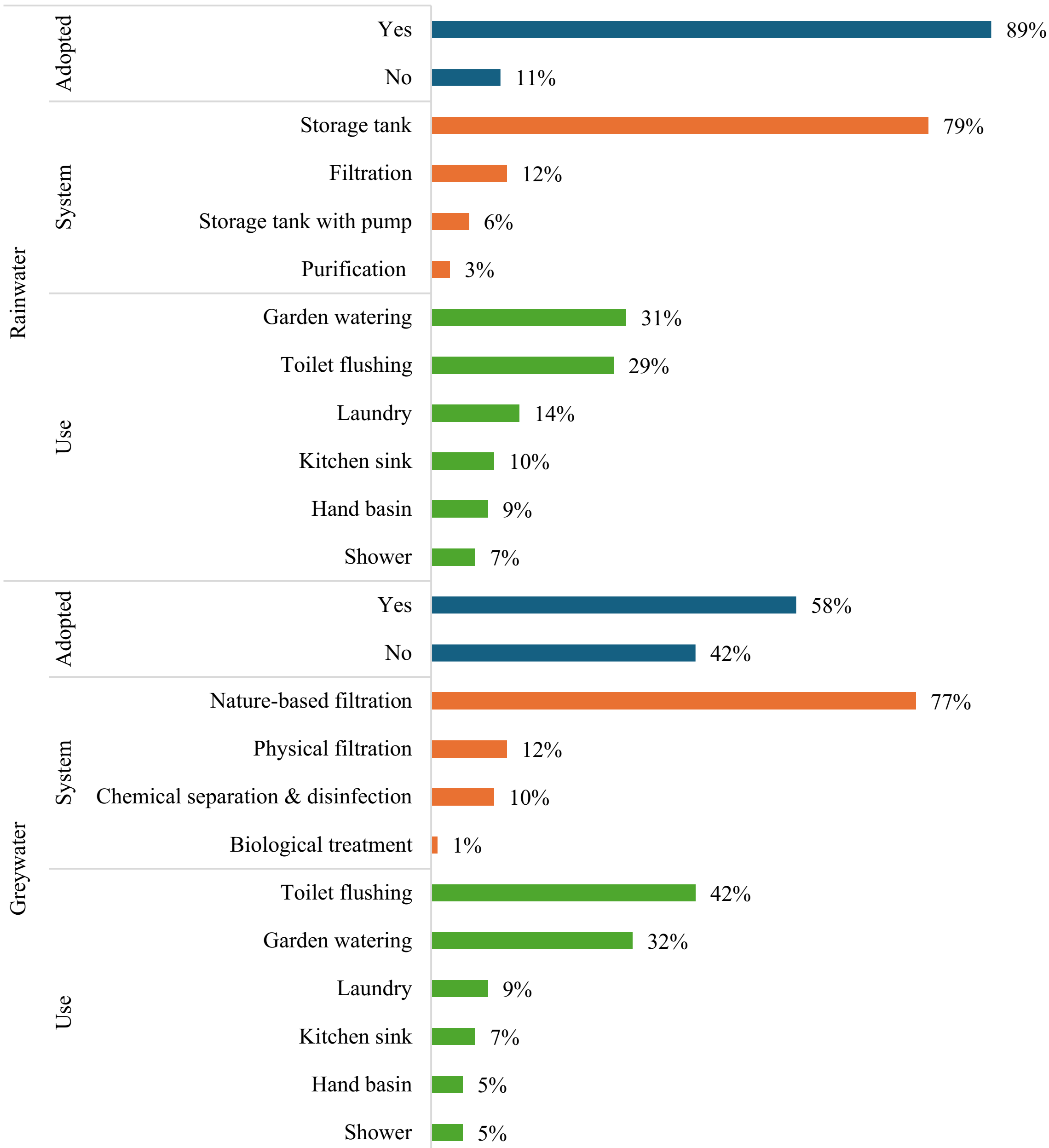


Fig. 5 water reuse systems information

technologies in the local market (18%), and the energy intensity of current systems (14%). These challenges, observed in residential properties, are documented by several scholars across various global South countries [24, 37, 41].

Conversely, the analysis of responses unveiled that Shortage of water/ drought (44%), water conservation (21%), environmental protection (14%), and cultural practices (10%) are the primary motivations driving South African property owners to install water recycling systems in their residential properties. These motivations are intricately linked to the social and environmental context of South Africa, notably the severe drought conditions famously known as "Day Zero" [52]. Moreover, the combination of these motivations underscores the crucial role of sociocultural factors in promoting water recycling systems in households, as emphasized by Stec and Słyś [13].

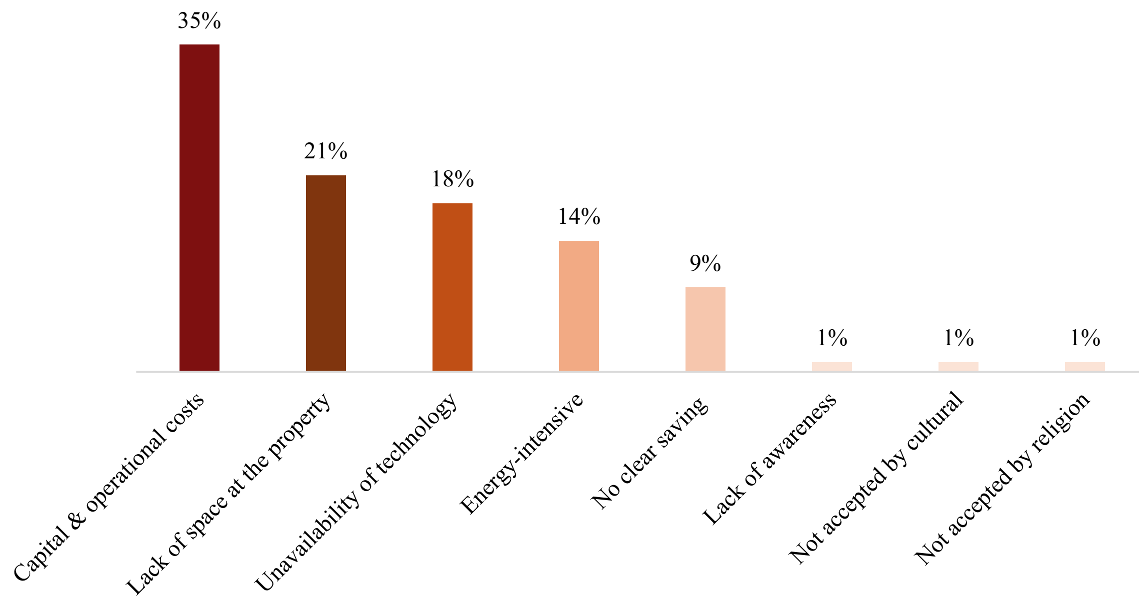


Fig. 6 Challenges on utilising water recycling

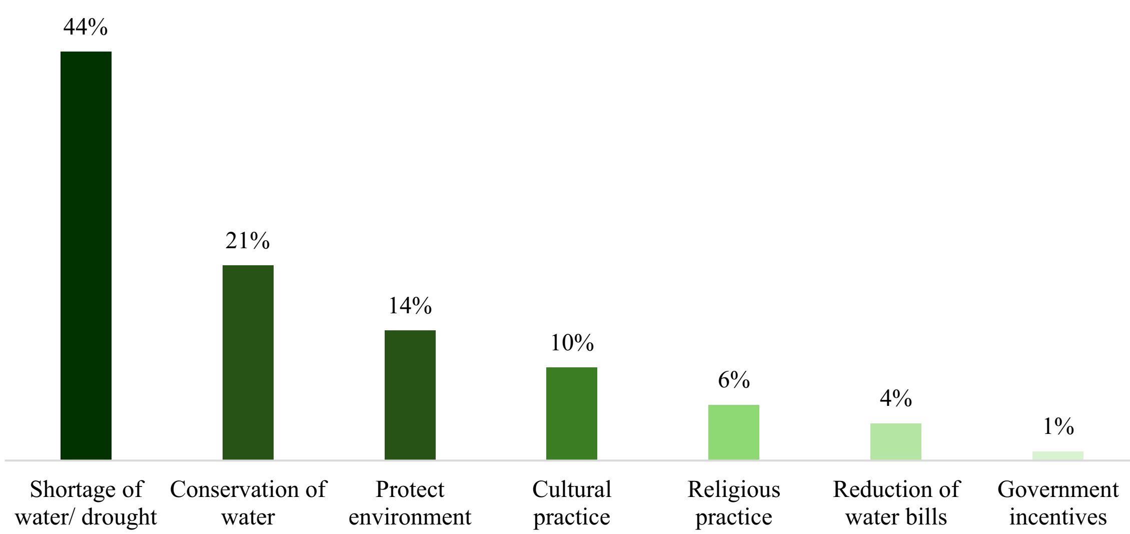


Fig. 7 Motivations on utilising water recycling

5.5 Modelling utilising water recycling systems

Prior to developing a causality model of water recycling system in South African residential properties the consistency and reliability of modelling components (constructs and subconstructs) are checked and the results are presented in Table 2.

The overall reliability and consistency test results shown that there is a good internal consistency between the relevant sub-constructs (0.7 < Cronbach's Alpha < 0.95, Cronbach's Alpha < rho-A < Composite Reliability). Also, the value of average variance (> 0.5) suggests that the constructs and sub-constructs have sufficient internal consistency and validity.

T-Statistic test was used to examine the research hypotheses (see Fig. 5) and the results are summarized in Table 3. The P-Values of all five hypotheses are less than 0.05, which is indicated all hypotheses are statistically significant.

The result of hypotheses testing validated that the level of adoption of water recycling systems in South African residential properties has a moderate positive associate with residential property characteristics, which also proved by Prins et al. [4] and Moghayedi et al. [34].

Table 2 Reliability and consistency of modelling components

Construct	Number of Variables	Internal consistency		Composite Reliability	Convergent validity (AVE)
		Cronbach's Alpha	rho_A		
Houses' characteristics & residents' awareness	8	0.779	0.786	0.788	0.771
Motivations on adoption of water recycling system	7	0.801	0.807	0.814	0.799
Challenges on adoption of water recycling system	8	0.792	0.802	0.807	0.788

Moreover, the hypothesis tests indicated a strong positive association between motivations for adopting water recycling systems and the level of adoption of water recycling systems, while the challenges have a moderate negative effect on the level of adoption of water recycling systems in South African residential properties as illustrated in Fig. 5. The comparison of path coefficients of motivations and challenges proved that the positive effect of motivations on adoption of water recycling systems in residential properties is considerably larger than the negative effect of challenges, which indicate that the level of adoption of water recycling systems in South African residential properties drive by socioenvironmental motivations.

The result of hypotheses test and analysis of indirect path analysis indicated that beside the direct positive and negative effects of motivations and challenges on level of adoption of water recycling systems, these two dependent constructs indirectly impact on the extent of utilising of water recycling systems in South African residential properties through residential property characteristics. These findings proved the moderating role of motivations and challenges on residential property characteristics. In the other the motivations and challenges of water recycling systems influence the South African on selecting properties.

Comparing the direct and indirect path coefficients of developed causality model shows the predominant role of motivations on the level of adoption of water recycling systems compared to residential property characteristics and challenges in South Africa.

As shown in Fig. 8, all loading factors of sub-constructs are greater than 0.7, which indicate the high relationships of sub-constructs to relevant construct and the reflective measurement of sub-constructs and the model. Moreover, the result of hypotheses test and analysis the association between dependent and independent constructs validate the high accuracy of developed causality model for adopting recycling system in South African residential properties.

In the final step, the outer weights of sub-constructs are calculated using multiple regression, and the results ranked according to their relative importance in Table 4.

As presented in Table 4, availability of space for installing water recycling system and type of house are the most important sub-constructs variable under characteristics of residential property. Shortage of water/drought, conservation of water and protect environment are the key sub-constructs of motivation constructs.

Considering the significant positive effect of motivation construct on the level of adoption of water recycling systems these three sub-constructs have the most influences on the extent of adopting water recycling in South African residential properties. On the other hand, capital and operational costs is the main barrier on adopting the water recycling systems in residential properties which verified with several researchers [1, 33, 34]. Additionally, the outer weights of sub-constructs validate the positive and negative effects of all defined sub-constructs on the level of adoption of water recycling systems in South African residential properties.

6 Conclusion

The current study empirically examines the associations between characteristics of residential property, motivations and challenges and level of adoption of water recycling systems in South African residential properties. The analysis of residential property characteristics, motivations and challenges and extent of use of water recycling in South African residential properties and modelling their associations validated the significant positive direct and moderate association of motivations and significant negative direct and moderate association of challenges as independent constructs on the level of adoption of water recycling systems in South African residential properties. The findings have proved that the strong positive effect of socioenvironmental motivations are the main factors for high level of utilising water recycling systems in South African residential properties. The findings also shown that unavailability of technology and

Table 3 T-Statistics test results

Hypothesis	Path Coefficient	T Statistics	P Values	Decision
H1: Residential property characteristics—> level of adoption of water recycling systems	0.744	4.407	0.001	Significant
H2: Motivations—> level of adoption of water recycling systems	0.558	11.850	0.000	Significant
H3: Residential property characteristics—> Motivations—> Level of adoption of water recycling systems	0.113	3.490	0.003	Significant
H4: Challenges—> level of adoption of water recycling systems	− 0.407	9.969	0.000	Significant
H5: Residential property characteristics—> Challenges—> Level of adoption of water recycling systems	− 0.123	3.901	0.002	Significant

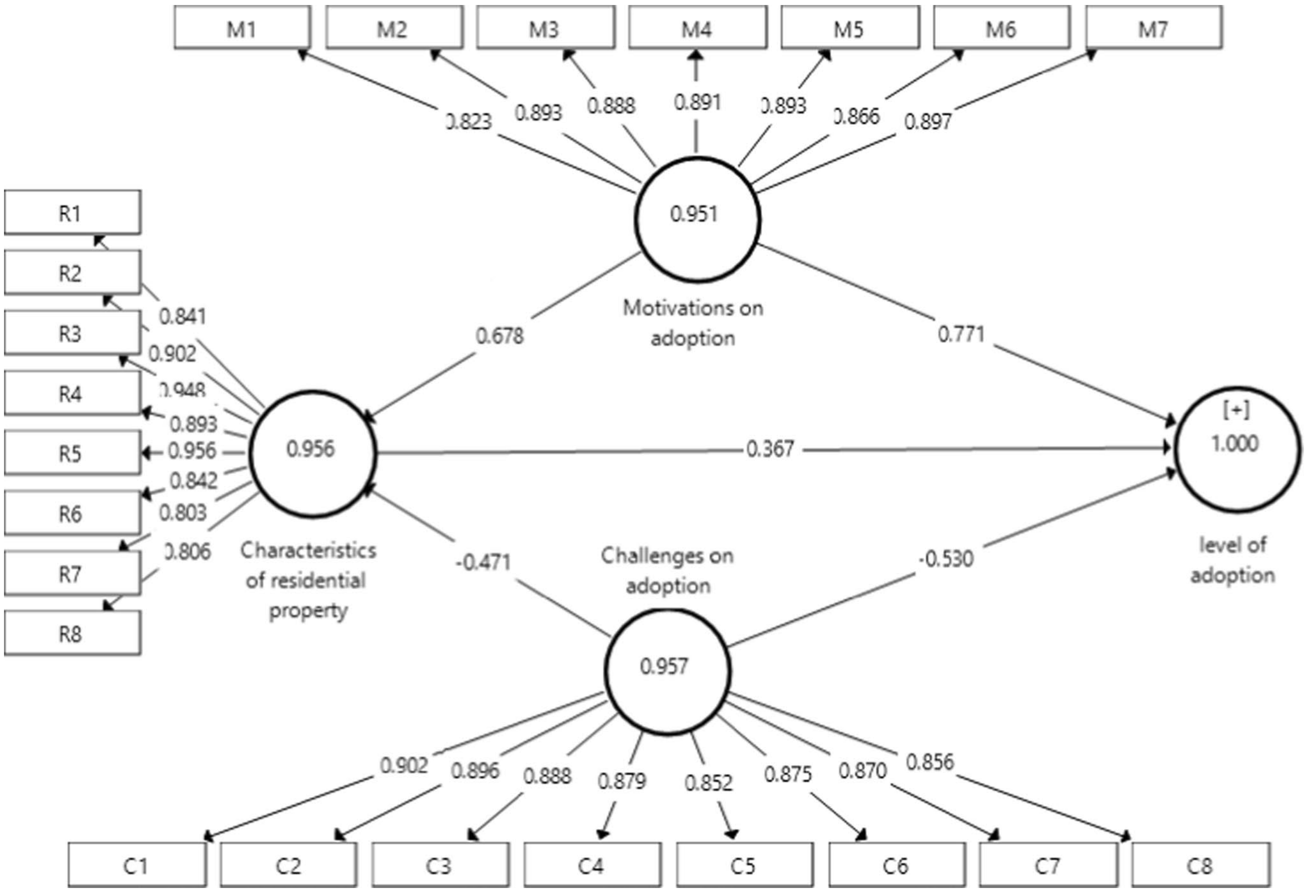


Fig. 8 Path analysis of causality model of water recycling system adoption

energy-intensity of existing system as main challenges are reduced the level of adoption, thus providing efficient water recycling systems in local market will be significantly increase the adoption of these systems in residential properties.

Based on these findings, it can conclude that the level of adoption of water recycling systems in South African residential properties will increase with educating of local society and make available more efficient water recycling systems in local market. The findings of the study also provide significant implications for future communication strategies to encourage the uptake of micro water recycling systems in residential properties. Therefore, the acquisition of technical knowledge associated with developing more efficient water recycling systems and the national and local government incentives for adopting water recycling systems in South Africa are recommended as the proper mechanisms to address the challenges and improve the utilising water recycling system in South African residential properties.

The findings of study and validated causality model can be used by local and national South African governments to comprehend the readiness of residential properties, awareness of local society, motivating or challenging factors likely to influence property owners to adopt and use water recycling systems in South Africa. The findings of study will be assisted the local technology providers in developing optimum water recycling systems based on the social, economic and environmental context of South Africa that satisfy the needs of property owners and at the same time enhance the sustainability of country. In the future study the validated causality model will be used to develop a data-driven decision-making toolkit to adopt the optimum water recycling systems in residential properties for South Africa.

7 Limitations and scope for further research

The study has some limitations that should be considered when interpreting the findings. Firstly, the geographical scope is confined to South African residential properties, which may limit the applicability of the results to other regions with different socio-economic and environmental contexts. Secondly, the data used in the study may not

Table 4 Outer weights of variables

Variables	Characteristics of residential property	Motivations	Challenges
Availability of space for installing water recycling system	0.237		
Type of house	0.194		
Wastewater system use in the house	0.165		
Availability of garden in the property	0.125		
Type of roof	0.111		
Water supply system in the property	0.092		
Age of house	0.085		
Affordability of water	0.025		
Shortage of water/drought		0.317	
Conservation of water		0.255	
Protect environment		0.221	
Cultural practice		0.153	
Religious practice		0.112	
Reduction of water bills		0.075	
Government incentives		0.014	
Capital & operational costs			− 0.271
Lack of space at the property			− 0.131
Unavailability of technology			− 0.129
Energy-intensive			− 0.122
No clear saving			− 0.081
Lack of awareness			− 0.055
Not accepted by religion			− 0.011
Not accepted by cultural			− 0.007

capture all variables influencing the adoption of water recycling systems, such as cultural or psychological factors, potentially affecting the comprehensiveness of the analysis. Lastly, the study does not extensively analyse the technical performance or cost-effectiveness of different water recycling technologies, which could provide a more detailed understanding of the practical challenges and benefits associated with these systems.

Future research should expand the geographical scope to include other regions, allowing for comparative studies that can enhance the understanding of global adoption patterns of water recycling systems. Additionally, there is a need to investigate the development and deployment of new water recycling technologies, with a focus on reducing costs, improving energy efficiency, and enhancing user-friendliness. Behavioral studies should also be conducted to explore the psychological and cultural factors influencing the adoption of water recycling systems, which can inform the design of more effective awareness campaigns and policies. Lastly, developing data-driven decision-making toolkits will be crucial in assisting property owners to select the most suitable water recycling systems based on their specific needs and local context.

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Author contribution AM conceived and designed the study conducted the literature review and performed the data collection and analysis. AM also developed causality model the structural equation modeling framework, interpreted the results, and drafted the manuscript. AM revised and approved the final version of the manuscript for submission. All aspects of this research were solely managed and completed by AM, ensuring the integrity and accuracy of the work presented.

Data availability The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate The study was conducted in accordance with the Declaration of University of Cape Town and approved by Ethics Committee of the Faculty of Engineering and Built Environment, University of Cape Town (Application Ref: 231,207 and 20 November 2022).

Consent for publication All participants involved in this study provided informed consent to participate prior to participation.

Competing interests The authors declare no competing interests.

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