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ANDRIANE DE MELO RODRIGUES

SISTEMA INTEGRADO DE RECICLAGEM DE ÁGUAS PLUVIAIS E CINZAS PARA ADAPTAÇÃO ÀS MUDANÇAS CLIMÁTICAS

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ATA DE DEFESA DE TESE

Ata Nº **DD006/2025** da sessão de Defesa de Tese de **Andriane de Melo Rodrigues**, que confere o título de Doutora em **Ciências Ambientais**, na área de concentração em **Estrutura e Dinâmica Ambiental.**

Aos **dez dias de julho de dois mil e vinte e cinco**, a partir das **oito horas**, na **Google Meet** <**https://meet.google.com/asn-imoa-sqe**>, realizou-se a sessão pública de Defesa de Tese intitulada **"SISTEMA INTEGRADO DE RECICLAGEM DE ÁGUAS PLUVIAIS E CINZAS: RESILIÊNCIA URBANA E ABASTECIMENTO DESCENTRALIZADO NA ADAPTAÇÃO ÀS MUDANÇAS CLIMÁTICAS"**. Os trabalhos foram instalados pela Orientador Doutor **Klebber Teodomiro Martins Formiga (EECA/UFG)** com a participação dos demais membros da Banca Examinadora: Doutora **Daniela de Melo e Silva (ICB/UFG), membro titular interno, cuja participação ocorreu através de videoconferência**; Doutora **Jussanã Milograna (IFG), membro titular externo, cuja participação ocorreu através de videoconferência**; Doutora **Ana Silvia Pereira Santos (DESMA/UERJ), membro titular externo, cuja participação ocorreu através de videoconferência**; Doutor **Sergio Almeida Pacca (USP), membro titular externo, cuja participação ocorreu através de videoconferência**. Durante a arguição os membros da banca **fizeram** sugestão de alteração do título do trabalho. A Banca Examinadora reuniu-se em sessão secreta a fim de concluir o julgamento da Tese tendo sido a candidata **aprovada** pelos seus membros.

Proclamados os resultados pelo Professor **Klebber Teodomiro Martins Formiga (EECA/UFG)**, Presidente da Banca Examinadora, foram encerrados os trabalhos e, para constar, lavrou-se a presente ata que é assinada pelos membros da Banca Examinadora, aos **dez dias de julho de dois mil e vinte e cinco**.

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RESUMO

As áreas urbanas enfrentam desafios crescentes relacionados ao abastecimento de água, intensificados pelos impactos das mudanças climáticas e pelo contínuo crescimento populacional. Nesse contexto, abordagens integradas que combinam a captação de água pluvial (*Rainwater Harvesting* — RWH) e o reuso de água cinza (*Greywater Reuse* — GWR) configuram-se como alternativas promissoras para fortalecer a resiliência hídrica urbana e promover uma gestão mais sustentável dos recursos hídricos. Diante desse cenário, esta tese tem como objetivo contribuir para o avanço do conhecimento e para o aprimoramento das práticas associadas à concepção, operação e avaliação de sistemas descentralizados e integrados de RWH e GWR em residências, com foco nos aspectos financeiros, ambientais e operacionais. Para alcançar esse propósito, foram definidos três objetivos específicos: (i) realizar uma revisão sistemática da literatura para identificar métodos de projeto, lacunas de conhecimento e tendências de pesquisa relacionadas a esses sistemas; (ii) monitorar o desempenho de um sistema integrado de RWH e GWR em funcionamento em uma residência em Rio Verde (GO), Brasil, avaliando a qualidade e a quantidade da água produzida, os ganhos em economia de água potável e a frequência de manutenção necessária; e (iii) analisar a relação custo-benefício desses sistemas em escala residencial, considerando os impactos ambientais por meio da Análise do Ciclo de Vida (ACV) e a viabilidade econômica com base em indicadores de custo. Os resultados obtidos demonstraram que as tecnologias complementares de aeração e desinfecção por radiação ultravioleta implementadas no sistema foram eficazes na remoção de matéria orgânica, eliminação de odores e inativação de coliformes termotolerantes, garantindo qualidade satisfatória da água para usos não potáveis. O monitoramento indicou uma economia de até 41% no consumo de água potável, destacando o potencial do sistema para reduzir a pressão sobre os recursos hídricos convencionais. A análise de ciclo de vida revelou melhorias significativas no desempenho ambiental, especialmente com o uso de energia renovável (fotovoltaica) para operar os dispositivos de tratamento e bombeamento. Além disso, os estudos de viabilidade econômica indicaram que o sistema se torna mais vantajoso financeiramente em cenários de maior demanda e uso intensivo da água reciclada, reforçando a importância de estratégias de dimensionamento adequado e conscientização do usuário. Assim, conclui-se que sistemas residenciais integrados de RWH e GWR são tecnicamente viáveis, ambientalmente vantajosos e economicamente atrativos em contextos urbanos, representando uma alternativa promissora para promover a resiliência hídrica e práticas mais sustentáveis de gestão da água. Recomenda-se, ainda, que políticas públicas incentivem a adoção dessas soluções por meio de subsídios, regulamentações específicas e programas de educação ambiental, potencializando seus benefícios em larga escala.

Palavras-chave: Abastecimento descentralizado; Resiliência urbana; Avaliação do Ciclo de Vida; Sustentabilidade hídrica; Gestão de águas urbanas.

ABSTRACT

Urban areas face increasing challenges related to water supply, which are exacerbated by the impacts of climate change and continuous population growth. In this context, integrated approaches that combine Rainwater Harvesting (RWH) and Greywater Reuse (GWR) have emerged as promising alternatives to enhance urban water resilience and promote more sustainable water resource management. Against this backdrop, this thesis aims to contribute to the advancement of knowledge and to the improvement of practices related to the design, operation, and evaluation of decentralized and integrated RWH and GWR systems in residential settings, with a focus on financial, environmental, and operational aspects. To achieve this goal, three specific objectives were established: (i) to conduct a systematic literature review to identify design methods, knowledge gaps, and research trends related to these systems; (ii) to monitor the performance of an integrated RWH and GWR system operating in a residential building in Rio Verde, Goiás, Brazil, evaluating the quality and quantity of the water produced, the savings in potable water consumption, and the required maintenance frequency; and (iii) to assess the cost–benefit ratio of such systems at the household scale, considering environmental impacts through Life Cycle Assessment (LCA) and economic feasibility based on cost indicators. The results demonstrated that the complementary aeration and ultraviolet (UV) disinfection technologies implemented in the system were effective in removing organic matter, eliminating odors, and inactivating thermotolerant coliforms, ensuring satisfactory water quality for non-potable uses. Monitoring showed up to a 41% reduction in potable water consumption, highlighting the system's potential to alleviate pressure on conventional water resources. The life cycle assessment indicated significant improvements in environmental performance, particularly when renewable (photovoltaic) energy was used to operate treatment and pumping devices. Moreover, the economic feasibility analysis showed that the system becomes financially more advantageous under scenarios of higher demand and intensive use of the recycled water, underscoring the importance of proper system sizing and user awareness. In conclusion, residential integrated RWH and GWR systems are technically feasible, environmentally beneficial, and economically attractive in urban contexts, representing a promising strategy to enhance water resilience and foster more sustainable urban water management practices. It is further recommended that public policies encourage the adoption of such solutions through subsidies, specific regulations, and environmental education programs, thereby maximizing their large-scale benefits.

Keywords: Decentralized supply; Urban resilience; Life Cycle Assessment; Water sustainability; Urban water management.

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LISTA DE SIGLAS E ABREVIATURAS

ABNT	Associação Brasileira de Normas Técnicas
AGWR	Australian Guidelines for Water Recycling
APHA	American Public Health Association
BA-MBR	Biorreator de membrana com aeração por bolhas (Bubble-Aerated Membrane Bioreactor)
BDD	Diamante Dopado com Boro (Boron-Doped Diamond)
BOD_5	Demanda Bioquímica de Oxigênio em 5 dias (Biological Oxygen Demand)
CFU	Unidades Formadoras de Colônia
COD	Demanda Química de Oxigênio
CONAMA	Conselho Nacional do Meio Ambiente
DRAB	Diretrizes para Reúso de Água no Brasil
EPA	Environmental Protection Agency (Agência de Proteção Ambiental dos EUA)
GWR	Reuso de Água Cinza (Graywater Reuse)
HDPE	Polietileno de Alta Densidade (High Density Polyethylene)
HDT	Tempo de Detenção Hidráulica (Hydraulic Detention Time)
IEC	Inteligência Eletrônica de Controle (no caso da plataforma Monitor IE)
INMET	Instituto Nacional de Meteorologia
IPCC	Painel Intergovernamental sobre Mudanças Climáticas
IRGRS	Integrated Rainwater and Graywater Recycling System
ISO	International Organization for Standardization
LED	Diodo Emissor de Luz (Light Emitting Diode)
MBR	Biorreator de membrana (Membrane Bioreactor)
MPN	Número Mais Provável (Most Probable Number)
NTU	Unidades Nefelométricas de Turbidez
POA	Processos Oxidativos Avançados
PP	Polipropileno (Polypropylene)
PVC	Policloreto de Vinila (Polyvinyl chloride

RWH	Captação de Água de Chuva (Rainwater Harvesting)
SDG	Objetivos de Desenvolvimento Sustentável (Sustainable Development Goals)
TDS	Sólidos Totais Dissolvidos (Total Dissolved Solids)
TON	Número de Odor Limite (Threshold Odour Number)
UV	Ultravioleta (Ultravioleta)
UV-C	Faixa do espectro UV com maior capacidade germicida (254 nm)
UV-LED	Lâmpada de Diodo Emissor de Luz Ultravioleta
WHO	World Health Organization (Organização Mundial da Saúde)

1 INTRODUÇÃO

No atual cenário de mudanças climáticas globais, a adaptação das cidades assume papel crucial na prevenção e mitigação de danos, além de fortalecer a resiliência urbana diante dos desafios climáticos em curso (Sharma et al., 2023; Daloğlu et al., 2023). O crescimento urbano acelerado e a pressão sobre as bacias hidrográficas já impõem obstáculos significativos, especialmente em função da crescente demanda por recursos hídricos (Wang, Xu, et al., 2023; Shao and Xu, 2023; Abellán et al., 2021).

A Região Centro-Oeste do Brasil, onde se localiza o município de Rio Verde (sudoeste de Goiás) — área de estudo desta pesquisa —, apresenta um regime climático marcado por extremos. Durante o verão (outubro a abril), são frequentes as chuvas intensas e tempestades concentradas em curtos períodos, com acumulados elevados que provocam alagamentos e riscos geo-hidrológicos. Já no período seco, entre maio e setembro, são comuns as estiagens prolongadas. Segundo o Anuário Climático do INPE (2019) e relatórios do CEMADEN (2024), esses eventos extremos têm se intensificado: a estação chuvosa vem apresentando precipitações cada vez mais irregulares e severas, enquanto o Índice Integrado de Seca (IIS3) revela que diversos municípios do Centro-Oeste enfrentaram secas de intensidade moderada a grave entre 2023 e 2024, comprometendo a disponibilidade hídrica e afetando diretamente a produção agrícola — atividade fundamental para a economia regional.

Essas alterações no regime hidrológico, associadas à crescente urbanização e à ocupação intensiva do solo, ampliam os desafios enfrentados pelos corpos hídricos em áreas urbanizadas. Nesse contexto, os mananciais hídricos exercem simultaneamente a função de abastecer os sistemas públicos de fornecimento de água e de receber efluentes residuais e pluviais. Como consequência, esses corpos d'água enfrentam desafios significativos relacionados à disponibilidade hídrica, tanto em termos de qualidade quanto de quantidade (Tao et al., 2023; Li et al., 2024). Além das fontes pontuais de poluição, os mananciais utilizados como fontes de abastecimento urbano estão igualmente sujeitos à contaminação difusa, proveniente tanto de áreas agrícolas — como o carreamento de fertilizantes e agrotóxicos — quanto de áreas urbanas, devido ao transporte de resíduos sólidos para os sistemas de drenagem pluvial e, consequentemente, para os corpos hídricos receptores (Hao et al., 2024; Peng et al., 2023; Kwakye et al., 2024).

A degradação dos mananciais e a variabilidade climática têm impulsionado a busca por novas fontes de abastecimento, especialmente durante períodos de estiagens prolongadas, quando os corpos d’água se aproximam dos limites das vazões ecológicas, aumentando os conflitos pelo uso da água. Nessas circunstâncias, é comum a adoção de soluções emergenciais, como a perfuração de poços artesianos em áreas residenciais para a extração de água subterrânea (Schuch et al., 2023). No entanto, tais práticas podem acentuar o desequilíbrio do ciclo hidrológico, resultando em impactos como degradação da qualidade da água, subsidência do solo, intrusão salina e alterações significativas no fluxo subterrâneo (Sharp Jr, 1997).

Diante dessas limitações, cresce o interesse por soluções descentralizadas, capazes de reduzir a dependência das fontes tradicionais e mitigar os impactos das crises hídricas. Nesse sentido, a adoção de sistemas integrados de reciclagem de água, como a captação de água de chuva (Rainwater Harvesting — RWH) e o reuso de água cinza (Greywater Reuse — GWR), configura-se como uma estratégia promissora para reduzir a demanda por água potável e aliviar a pressão sobre os sistemas convencionais de abastecimento, contribuindo para a sustentabilidade hídrica das cidades (Keller, 2023).

Nem todas as atividades domésticas e comerciais em edificações urbanas requerem água potável da rede pública, sendo plenamente viável utilizar essas fontes alternativas para fins não potáveis, como irrigação de jardins, lavagem de pisos e descargas sanitárias (Leong et al., 2018; Marinoski and Ghisi, 2019; Tamagnone et al., 2020). Além de diversificar as fontes de suprimento, esses sistemas também contribuem para reduzir o volume de águas pluviais direcionado à drenagem urbana, mitigando riscos de inundações e aliviando a pressão sobre as reservas de água superficial e subterrânea (Hdeib and Aouad, 2023; Keller, 2023).

Apesar de seus benefícios reconhecidos, esses sistemas ainda são subutilizados nos contextos urbanos contemporâneos, sobretudo em países em desenvolvimento. Isso se deve, em parte, à predominância de uma infraestrutura urbana concebida para redes de abastecimento convencionais e centralizadas (Li et al., 2021). Diante dessa realidade, é essencial aprofundar o conhecimento sobre o desempenho real desses sistemas, identificar os pontos críticos que afetam sua eficiência e viabilidade, e avaliar tecnologias complementares de tratamento capazes de assegurar a qualidade adequada da água para usos não potáveis, mesmo em condições climáticas adversas.

Desse modo, esta tese foi estruturada em três estudos complementares, com o propósito de aprofundar o conhecimento técnico e científico e de fomentar a adoção de sistemas integrados de captação de águas pluviais (Rainwater Harvesting Systems — RWH) e reuso de água cinza (Greywater Recycling — GWR) em contextos urbanos. O primeiro artigo consiste em uma revisão sistemática voltada a mapear as lacunas de conhecimento, as diretrizes de projeto e as tendências de pesquisa sobre esses sistemas; essa análise abrangente do estado da arte evidenciou limitações relevantes — por exemplo, quanto à combinação sinérgica entre fontes pluviais e águas cinzas, aos requisitos de tratamento, à qualidade final da água e ao desempenho ambiental e econômico —, ressaltando a necessidade de investigações empíricas adicionais para otimizar o projeto e aferir de forma mais abrangente os benefícios associados.

O segundo artigo aborda o monitoramento, em escala real, de um sistema residencial integrado, examinando o balanço hídrico, a eficiência das tecnologias complementares de tratamento por meio da qualidade da água reciclada, a economia efetiva de água potável obtida e a frequência de manutenção requerida. Os resultados fornecem evidências práticas robustas sobre o potencial de redução do consumo de água da rede pública, além de oferecer subsídios técnicos para aprimorar parâmetros operacionais, apoiar a elaboração de manuais e orientar iniciativas de regulamentação para o reuso descentralizado.

Por fim, o terceiro artigo aplica uma Avaliação do Ciclo de Vida (ACV) associada a uma avaliação econômica, explorando diferentes cenários de demanda, níveis de consumo da água reciclada e fontes de energia elétrica para o funcionamento do sistema monitorado. Essa abordagem integrada possibilita comparar o desempenho ambiental e os custos operacionais das alternativas de tratamento, identificando soluções mais sustentáveis e economicamente viáveis.

Assim, os três estudos reunidos nesta tese contribuem de forma original para o avanço do conhecimento científico, oferecem recomendações práticas de operação e manutenção desses sistemas voltadas a profissionais e gestores, e fornecem bases consistentes para o desenvolvimento de políticas públicas que incentivem a implementação de sistemas descentralizados de reuso. Dessa forma, promovem maior resiliência hídrica urbana e o uso racional dos recursos hídricos, especialmente diante dos desafios impostos pelas mudanças climáticas.

2 OBJETIVOS

2.1 Objetivo Geral

Contribuir para o avanço técnico-científico e prático dos sistemas integrados de reciclagem de águas pluviais e cinzas descentralizados, promovendo sua viabilidade operacional e econômica, fornecendo subsídios para a formulação de instrumentos normativos, manuais técnicos e políticas públicas voltadas à gestão sustentável das águas urbanas, de modo a favorecer sua ampla adoção.

2.2 Objetivos Específicos

1. Realizar uma revisão sistemática da literatura para identificar métodos, critérios de projeto, lacunas de conhecimento e tendências de pesquisa no campo dos sistemas descentralizados e integrados de reciclagem de águas pluviais (*Rainwater Harvesting System* — RWH) e águas cinzas (*Greywater Reuse System* — GWR), proporcionando uma visão abrangente e atualizada que apoie a identificação de desafios, oportunidades e instruções para futuras pesquisas e aplicações práticas (Capítulo 1).

2. Monitorar, em escala real, um sistema integrado de reciclagem de águas pluviais e cinzas, instalado em uma residência no município de Rio Verde, Goiás, Brasil, avaliando a quantidade e a qualidade da água produzida, a economia no consumo de água potável oriunda da rede pública e a frequência ideal de manutenção, a fim de gerar informações empíricas sobre o desempenho operacional e os benefícios dessa tecnologia, contribuindo para a elaboração de manuais técnicos e orientações operacionais para sua replicação em contextos urbanos (Capítulo 2).

3. Avaliar o desempenho ambiental e a viabilidade econômica de sistemas integrados de reciclagem de águas pluviais e cinzas em escala residencial, por meio da Avaliação do Ciclo de Vida (ACV) e de indicadores de custo, considerando diferentes cenários de demanda para o uso da água reciclada e distintas fontes energéticas para a operação do sistema, com o objetivo de fornecer subsídios técnicos para a tomada de decisão quanto ao projeto, à implementação de tecnologias e à elaboração de instrumentos normativos (Capítulo 3).

3 CONTRIBUIÇÃO PESSOAL

O tema desta pesquisa surgiu durante a disciplina de “Oficinas”, na qual eu deveria definir o escopo do projeto de tese. Por coincidência, esse processo ocorreu simultaneamente ao período de construção da minha própria residência, o que despertou meu interesse prático e acadêmico pelas soluções sustentáveis de gestão de águas urbanas.

Desde o início, desejei que a casa fosse cercada por um grande jardim, com horta e pomar, promovendo a integração entre infraestrutura e natureza de forma harmoniosa. A proposta era aliar conforto térmico, bem-estar, produção de alimentos orgânicos e sustentabilidade, por meio de soluções arquitetônicas e tecnologias ambientais que maximizassem o uso racional dos recursos naturais. Como engenheira ambiental, apaixonada por tecnologia, experimentação e criatividade — traços que também refletem meu perfil neurodivergente, com TDAH, autismo (nível 1) e altas habilidades — encarei o projeto da casa como uma extensão da minha crença de vida, unindo o autocuidado ao cuidado com a natureza e reafirmando meu compromisso com um futuro mais sustentável e com cidades que priorizem infraestruturas verdes. No entanto, ao optar por um jardim funcional, percebi que o consumo de água potável seria elevado, o que implicaria custos significativos e aumentaria a vulnerabilidade da residência diante de períodos de estiagens prolongadas —cada vez mais frequentes, em função da intensificação das mudanças climáticas.

Diante desse cenário, surgiu a ideia de reaproveitar as águas cinzas provenientes do chuveiro e da máquina de lavar, integrando essa estratégia ao uso de técnicas de amortecimento de cheias. Essa escolha também foi influenciada pela decisão de realizar a pesquisa sob orientação de um professor com ampla experiência em drenagem urbana. Além da escassez hídrica, o período chuvoso na região é marcado por chuvas intensas e consecutivas, frequentemente associadas a inundações em córregos urbanos canalizados, como o Barrinha e o Sapo. A captação de água de chuva mostrou-se, assim, uma solução ideal: além de reduzir a sobrecarga sobre a infraestrutura de drenagem, permitiria o armazenamento de água para uso no jardim e na limpeza de pisos durante a seca — período caracterizado por intensa deposição de material particulado, decorrente da colheita nas áreas agrícolas do entorno, de ventos fortes e de queimadas que, embora façam parte de práticas culturais locais, têm se intensificado nos últimos anos em função de condições climáticas mais extremas e imprevisíveis.

Essa motivação pessoal, conectada ao desejo por soluções sustentáveis e resilientes, deu origem ao primeiro artigo da tese. Com o objetivo de compreender o estado da arte dos sistemas integrados e descentralizados de captação de águas pluviais (*Rainwater Harvesting System* — RWH) e reúso de águas cinzas (*Greywater Recycling System* — GWR) em contextos residenciais, realizei uma revisão sistemática da literatura. A análise revelou que a maioria dos estudos investiga esses sistemas de forma isolada, geralmente com reservatórios, tratamentos e formas de abastecimento distintos e, em muitos casos, descarta as águas cinzas mesmo após o tratamento por precauções sanitárias.

Essa prática se baseia, em grande parte, na recomendação de Liu et al. (2010), segundo a qual o tempo de armazenamento da água cinza bruta não deve ultrapassar 24 horas, devido ao risco de proliferação microbiana e à formação de compostos malcheirosos. No entanto, essa orientação tem sido frequentemente interpretada de forma restritiva por diversos autores (Birks et al., 2004; Dixon et al., 1999; Ryan et al., 2009; Markovič, 2018; Leong et al., 2017; Wanjiru & Xia, 2018; Chen et al., 2022), levando ao descarte da água cinza mesmo após tratamento avançado e desinfecção — como no estudo de Chen et al. (2021), que adota essa diretriz de forma literal. Entendo que essa recomendação seja apropriada para águas cinzas não tratadas.

Contudo, seu uso generalizado compromete o aproveitamento do potencial hídrico das águas cinzas tratadas, restringindo avanços na integração entre RWH e GWR e evidenciando uma lacuna importante a ser explorada por estudos mais aplicados e realistas.

A partir dessa lacuna, propus e investiguei, no segundo artigo, um sistema integrado de reciclagem de águas pluviais e cinzas — denominado Integrated Rainwater and Greywater Recycling System (IRGRS) — no qual ambas as águas são armazenadas em um único reservatório subterrâneo híbrido. Essa configuração favorece a diluição de contaminantes orgânicos, cor, turbidez e odor durante os períodos chuvosos, além de garantir maior estabilidade estrutural ao reservatório, evitando sua ociosidade durante a seca. Isso assegura a continuidade da disponibilidade de água não potável mesmo em períodos de estiagem prolongados.

Ainda conforme identificado na revisão, observou-se a escassez de estudos que monitorassem a qualidade da água ao longo de diferentes períodos climáticos. Por isso, decidi acompanhar o desempenho do IRGRS ao longo de um ano hidrológico completo, avaliando a qualidade e a quantidade de água produzida, a economia no consumo de água potável da rede pública e a frequência ideal de manutenção. No início do monitoramento, o sistema não contava com aeração durante o armazenamento nem com desinfecção por radiação ultravioleta (UV). Essas tecnologias complementares foram incorporadas posteriormente, com o avanço da estiagem. A ausência das chuvas resultou no aumento da concentração de coliformes termotolerantes e no surgimento de odores desagradáveis na água reciclada.

Diante desse cenário, adotaram-se a aeração e a desinfecção por UV para prolongar o armazenamento seguro da água cinza, aprimorar sua qualidade microbiológica e eliminar odores. Os resultados evidenciaram o sucesso da estratégia, ao evitar o descarte precoce (antes recomendado em até 24 horas), aumentar a eficiência do sistema — garantindo o suprimento para todos os usos não potáveis durante seis meses sem chuva — e ampliar a aceitação social, sobretudo pela eliminação dos odores perceptíveis.

Além disso, considero um diferencial deste estudo o uso da água reciclada para irrigação de hortaliças e frutíferas consumidas cruas, promovendo sinergia com os Objetivos de Desenvolvimento Sustentável (ODS), especialmente os relacionados à segurança hídrica e alimentar.

Outra questão que despertou meu interesse surgiu durante uma roda de conversa que ministrei na Semana de Engenharia do IF Goiano – Campus Rio Verde, onde atuo como docente. Na ocasião, alunos que trabalhavam ou estagiavam em construtoras relataram que projetos com reservatórios para captação de água de chuva eram frequentemente descartados por arquitetos, principalmente por questões estéticas. Diante desse cenário, busquei demonstrar, por meio deste trabalho e das imagens apresentadas abaixo (Fotografias 1 e 2), que é plenamente viável integrar reservatórios subterrâneos e o tratamento em *wetlands* de forma paisagisticamente atrativa, inclusive em residências de alto padrão, agregando valor ambiental, funcional e estético aos projetos arquitetônicos.

Fotografia 1. Imagem registrada em junho de 2025 da *wetland* construída (reservatório circular com bordas em tijolo aparente), vegetada com papiro-anão.

Por fim, a ideia do terceiro artigo surgiu ao perceber que, durante o período chuvoso, o sistema apresentava subutilização da água reciclada, o que indicava um potencial significativo para a ampliação da demanda. Esse diagnóstico motivou a avaliação de diferentes cenários de demanda para o consumo de água reciclada em usos finais não potáveis, tais como limpeza externa, descargas sanitárias, lavagem de roupas e reposição ou limpeza de filtros de piscinas.

Fotografia 2. Imagem registrada em junho de 2025 do reservatório subterrâneo destinado ao armazenamento e à aeração de águas pluviais e cinzas.

Além disso, observei que, embora o sistema dispensasse o uso de produtos químicos, o consumo energético associado à operação automatizada era elevado, o que poderia comprometer a economia obtida com a redução do consumo de água potável. Diante disso, decidi integrar à pesquisa uma avaliação do desempenho ambiental e econômico, considerando a operação do sistema descentralizado com duas fontes de energia: a rede de transmissão convencional e o sistema de energia solar fotovoltaica instalado na residência.

Assim, o terceiro artigo ampliou o escopo da pesquisa ao realizar uma Avaliação do Ciclo de Vida (ACV) e uma análise de viabilidade econômica, considerando diferentes cenários de demanda por água reciclada e distintas fontes de energia aplicadas a um mesmo sistema. Essa abordagem representa um avanço em relação aos estudos anteriores, que geralmente comparam sistemas de captação de água da chuva (RWH) e reuso de água cinza (GWR) com o abastecimento centralizado. No entanto, é importante destacar que o objetivo desses sistemas não é substituir o abastecimento convencional, mas sim atuar como estratégias complementares, reforçando a oferta hídrica e contribuindo para uma gestão mais sustentável dos efluentes pluviais e residuários.

Ao considerar a operação real de um sistema integrado e descentralizado, esta pesquisa buscou identificar os cenários mais eficazes de utilização, evidenciando estratégias que maximizem o aproveitamento de águas captadas e subutilizadas. O acúmulo dessas águas, além de limitar a capacidade dos reservatórios para amortecer cheias, representa desperdício de um recurso valioso. Simultaneamente, o uso eficiente contribui para reduzir a pressão sobre os corpos hídricos e mitigar os riscos de escassez nas áreas urbanas.

Outro aspecto inovador desta pesquisa é a utilização de medidores inteligentes, que permitem o monitoramento contínuo do sistema e fornecem dados em tempo real. Esse recurso possibilita a realização de análises detalhadas do balanço hídrico, contribuindo para uma melhor compreensão do desempenho operacional do IRGRS. Além disso, amplia significativamente o potencial de replicabilidade e adaptação do sistema a diferentes contextos urbanos, considerando suas particularidades climáticas, espaciais e infraestruturais.

A ausência de regulamentações específicas para a qualidade da água destinada ao reuso não potável reforça a relevância desta tese, que oferece subsídios técnicos consistentes à formulação de diretrizes normativas, visando à adoção de práticas de reuso seguras, eficientes e economicamente viáveis. Nesse contexto, o IRGRS configura-se como uma solução promissora para conservar recursos hídricos, fortalecer a resiliência urbana frente às mudanças climáticas e subsidiar o desenvolvimento de políticas públicas voltadas à gestão sustentável da água.

Adicionalmente, o sistema IRGRS foi encaminhado para registro de patente de processo e desenho técnico junto ao Instituto Nacional da Propriedade Industrial (INPI), reforçando seu caráter inovador e sua aplicabilidade prática. Essa iniciativa visa garantir a proteção intelectual da solução proposta, ao mesmo tempo em que abre caminho para sua difusão controlada e replicação em diferentes contextos urbanos.

Com base nos resultados obtidos, pretendo traduzir os achados desta pesquisa em um manual técnico direcionado aos gestores públicos da cidade de Rio Verde (GO), com orientações práticas sobre o projeto, operação e manutenção de sistemas integrados de reciclagem de águas pluviais e cinzas. O objetivo é que esses conhecimentos sirvam de base para a formulação de políticas públicas locais, incentivando a implementação de soluções descentralizadas de reuso em áreas urbanas e promovendo, assim, uma gestão hídrica mais inteligente, inclusiva e adaptativa.

Por fim, com base nos resultados obtidos e nas lacunas ainda existentes, identifico caminhos promissores para o aprofundamento desta linha de pesquisa, os quais não puderam ser plenamente explorados durante o tempo limitado do doutorado. Pretendo desenvolver, juntamente com futuros orientandos no Programa de Pós-Graduação em Engenharia Aplicada e Sustentabilidade (PPGEAS), no qual almejo atuar como docente, pesquisas complementares voltadas à aceitabilidade social dos sistemas de reuso, por meio da aplicação de questionários em diferentes regiões da cidade, considerando variáveis sociais como raça, gênero, renda e escolaridade, com o objetivo de identificar áreas estratégicas para a implementação de soluções descentralizadas com equidade e justiça socioambiental.

Além disso, pretendo elaborar um artigo voltado à operação inteligente do reservatório de armazenamento, com foco na sua otimização para o esvaziamento estratégico antes de eventos de chuva intensa, visando maximizar a captação e reduzir o escoamento superficial. Para subsidiar a tomada de decisão quanto ao momento ideal de esvaziamento ou retenção, empregarei técnicas de análise multicritério, capazes de ponderar variáveis climáticas, hidrológicas, operacionais e de demanda em diferentes cenários de uso da água reciclada. Simultaneamente, a estratégia deverá assegurar o armazenamento necessário para enfrentar veranicos e períodos prolongados de seca, promovendo a eficiência do sistema tanto em contextos de excesso quanto de escassez hídrica.

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CHAPTER I – INTEGRATED SYSTEMS FOR RAINWATER HARVESTING AND GREYWATER REUSE: A SYSTEMATIC REVIEW OF URBAN WATER MANAGEMENT STRATEGES

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Abstract

When combined, decentralized systems for rainwater harvesting and greywater reuse may enhance the water security of urban areas by reducing dependence on the mains water supply, in particular during critical periods, such as the dry season. These combined systems may also minimize the risk of flooding during the rainy season. The present study assesses the accumulated knowledge of these combined water recovery systems based on a systematic review of the scientific literature. The review revealed knowledge gaps that must be resolved to better assess the optimum combination of rainwater and greywater recovery, how this affects the need for the treatment of the recovered water, its final quality, potential options for reuse, water economy, and the environmental and economic performance of the system. Further empirical studies are required to determine the most adequate design configuration for these systems, considering their multiple objectives, technological perspectives, and in particular, their potential for improving environmental shortcomings. There is a clear need for widespread use of low-impact technologies to ensure the most effective possible results. Water recovery systems will become increasingly important as a means of tackling the challenges of water supplies in the urban landscape, which are being exacerbated by climate change.

Keywords: Rainwater capture, greywater reuse, stormwater management, minimization of wastewater, sustainable urban water systems, water conservation.

1. INTRODUCTION

The sixth report of the IPCC (2021) concluded that critical environmental scenarios are expected by the year 2050, with the availability of water resources in watersheds, including urban areas, being impacted globally by anywhere from 42% to 79% This will further exacerbate the vulnerability of urban water services during extreme weather conditions, in particular, in underdeveloped countries.

The diversification of water sources in urban areas may be one alternative solution for these problems. Rainwater Harvesting (RWH) and Graywater Reuse (GWR) systems are currently the two types of decentralized system that are being investigated most widely throughout the world (Stang et al., 2021). These systems can either operate independently or be connected to a central water supply service system, helping to minimize water stress, improve sustainability, and contribute to the resilience of the central system (Maskwa et al., 2021).

Decentralized RWH and GWR systems can provide a fundamentally important contribution to urban water networks, including the potable, pluvial, and sewage systems. In particular, the implementation of both RWH and GWR systems can reduce the demand for potable water. In addition, RWH systems can contribute to a reduction in the volume and intensity of rainwater runoff (Zhang et al., 2009; Zhang et al., 2010; Zanni et al., 2019), while GWR systems reduce the amount of sewage channeled to treatment plants by collecting greywater (domestic wastewater that does not contain significant amounts of feces or other c contaminants) for processing and use in specific applications (López Zavala et al., 2016; Penn et al., 2013; Marinoski and Ghisi, 2019; Zhang et al., 2021).

An RWH system captures rainwater from impermeable roofs and other surfaces, and stores this water for specific uses. While harvested rainwater can reduce the demand for water supplies, rainfall is irregular and the size of the roofs and storage reservoirs will limit the potential for savings of potable water (Ghaffarian Hoseini et al., 2016; Ghisi and Oliveira, 2007; Leong et al., 2017). By contrast, a GWR system collects and processes the wastewater produced by a household or building, which tends to be produced at a relatively constant rate throughout the year (Ghisi and Ferreira, 2007; Leong et al., 2018b). Greywater is wastewater produced by bathing and washing, rather than toilets, and thus has a reduced load of organic matter, including nutrients and pathogens (Pidou et al., 2007).

The combination of RWH and GWR systems is considered to be a highly efficient and cost-effective strategy for reducing the consumption of potable water (Gómez-Monsalve et al., 2022; Leong et al., 2018a; Wanjiru and Xia, 2018; Oviedo-Ocaña et al., 2018; Zhang et al., 2021). The combination of systems permits the continuous generation of non-potable water, by alternating between the increased capture of rainwater during rainy periods and the reuse of greywater during drier periods (Leong et al., 2018b).

While research on the combination of RWH and GWR systems has progressed considerably in recent years, the available data have yet to be reviewed systematically for the identification of recent trends and the consolidation of the information on the integration of these systems. This limits the understanding of the benefits of this innovative approach, and up to a point, restricts the more widespread implementation of this technology.

In this context, the present study reviewed the available literature to identify current trends in the combination of RWH and GWR systems, methods used and the criteria adopted for the design of projects, as well as the existence of potential knowledge gaps in this field of research. Overall, the study aims to compile the principal practical applications of the approach and the perspectives for research on the combination of these systems.

2. METHODS

The first step in the present study was a systematic review of the published literature on combined RWH and GWR systems. A systematic review provides a reliable approach for the collection and processing of data, given that it is a rigorous method that minimizes the risk of bias, while also identifying research or knowledge gaps that should be addressed in future studies (Petticrew and Roberts, 2008; Rubak et al., 2005). Up to now, there has never been a systematic review of the published data on the design, characteristics or analysis of the performance of combined RWH and GWR systems. This means that the present study can provide important insights for the understanding of the potential of this approach, and in particular, the identification of opportunities for future research and development.

This review was based on the Cochrane approach, supported by a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist (Moher et al., 2015). The StArt (State of the Art through Systematic Review) software, produced by the Software Research Laboratory at the Federal University of São Carlos (LaPES-UFSCar), was also used as an auxiliary search tool.

The first step in the application of this approach is the definition of the questions to be examined. The present study evaluated the following questions:

What are the principal design characteristics of the Rainwater Harvesting (RWH) and Greywater reuse (GWR) systems?

What are the principal research topics on RWH and GWR systems covered in the published literature?

What are the current limitations of RWH and GWR systems, as shown in the literature, and how can they be overcome in future research?

The literature searches focused on three databases – Scopus, the Web of Science, and Engineering Village (Compendex), and the first step in the process was to define the keywords most relevant to the objectives of the present study. A preliminary analysis of the literature revealed that "rainwater harvesting" was the term used most commonly to describe RWH systems, while "greywater reuse" or "greywater recycling" were used most frequently to designate GWR systems. Given this, the first search string included keywords "rainwater harvesting", "rainwater", and "rain water", while the second string was based on the "greywater reuse", "greywater recycling", "greywater", and "gray water". The terms "water conservation", "water reuse", "water recycling", "water savings", and "water supply" were included as a third search string, given that they are frequently used in the literature on the topics targeted in the present study.

No restrictions were applied to the search, in terms of the study year, region or type of document, although only publications written in English were considered. Duplicate publications found in different databases were not included in the analyses (i.e., one entry per publication). Initial screening was based on the content of the title and abstract, with subsequent screening focusing on the full text. If the reading of the full text found that the paper did not align with the objectives of the study or did not satisfy the inclusion criteria, the paper was excluded from the analyses.

There were two inclusion criteria, which were applied at each stage of the process: (i) studies that refer to the design, implementation or evaluation of RWH and GWR systems, and (ii) studies that refer to combined RWH-GWR systems. There were five exclusion criteria, which were applied to remove inappropriate papers from the analyses: (i) studies that are not related directly to the research topic; (ii) papers that do not present pertinent information on the implementation or evaluation of combined RWH-GWR systems; (iii) papers lacking the full text; (iv) summaries, brief reports or posters, and (v) studies that refer only to one of the systems (RWH or GWR). The data extracted from each paper were fed into an Excel spreadsheet for processing and analysis of biometric parameters and content.

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis

A total of 613 papers were identified in the literature search based on the initial search criteria. Almost half of these publications were eliminated in the first screening, however, due to their duplication in the different databases (Figure 1). At the end of the screening, based on the PRISMA analysis of their content, 41 papers were considered to be directly relevant to the objectives of the present study.

The Scopus database provided the largest number of candidate publications, with 256 (41.8% of the total, including duplicates), and also contributed most to the final total, with 37 (90.2%) of the 41 papers in the final list (Figure 1). The Web of Science database returned the next largest number of candidate publications (185, 30.1% of the total) and 30 (73.2%) of the papers included in the analyses, while Engineering Village provided 172 (28.0%) candidate publications, and 15 (36.6%) on the final list.

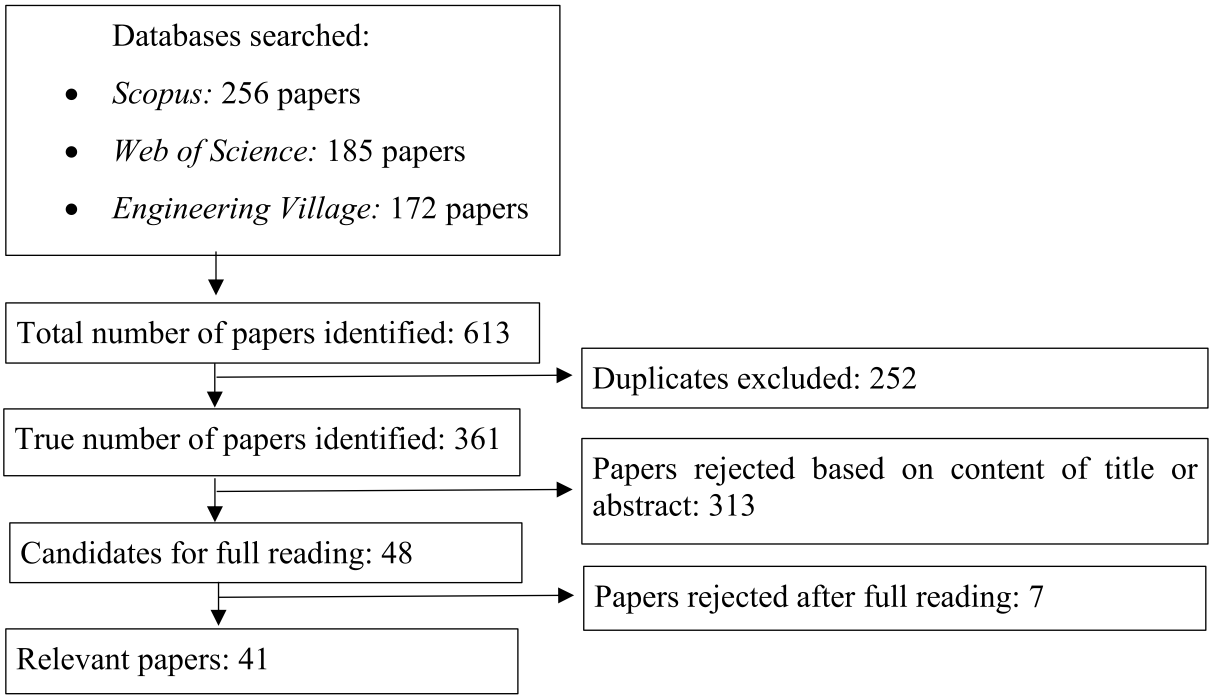

Figure 1. Flowchart of the literature review process using the PRISMA checklist approach (Moher et al. 2015).

Most of the selected papers (n = 29; 70.7%) were duplicated in at least two of the databases (Figure 2), while the others were listed in only one. The Scopus database had eight exclusive papers, while Web of Science had three, and Engineering Village, only one exclusive publication.

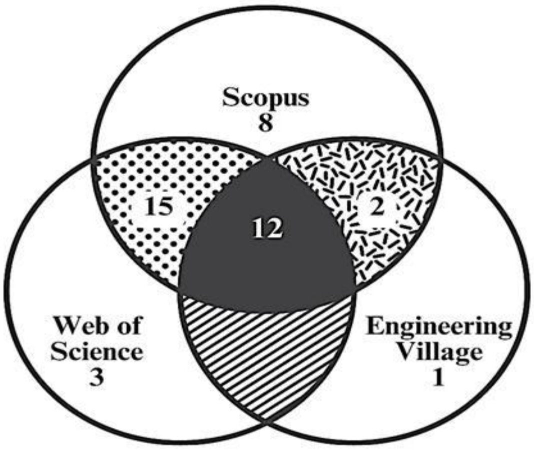

Figure 2. Venn diagram showing the distribution of the 41 selected papers among the different databases surveyed in the present study.

Brazil was the location of the most studies of any country, with eight papers (Figure 3), followed by Malaysia and the United Kingdom, each with four papers, while Australia, Colombia, Poland, and the United States were each the location of three studies. No more than two papers were identified in any of the 11 other countries included here.

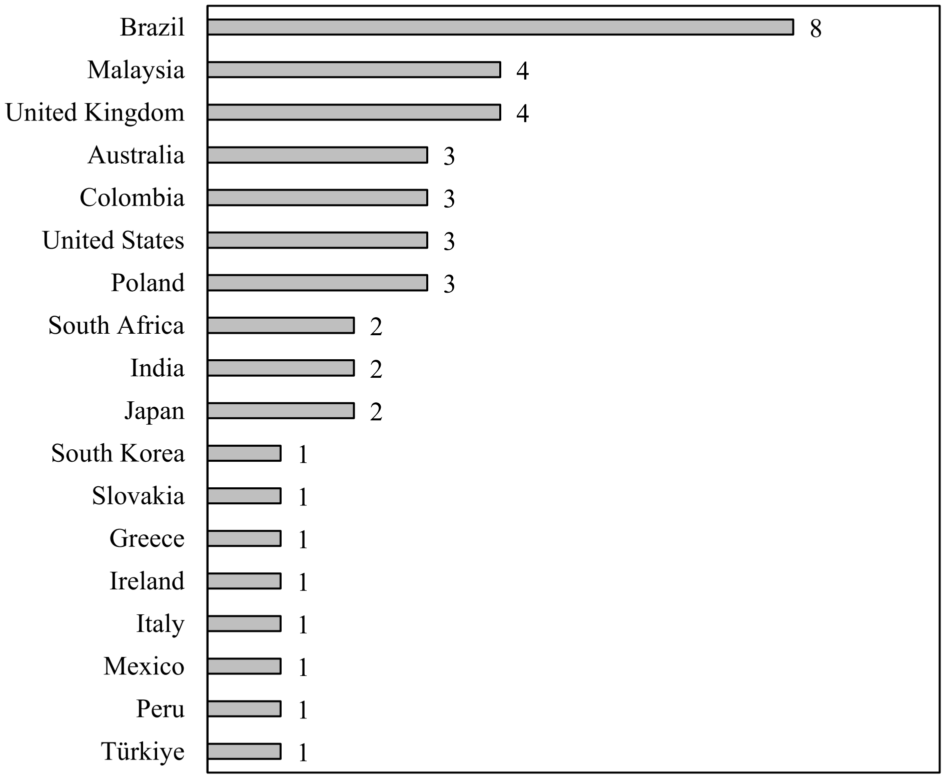

Figure 3. The number of studies per country, considering the 41 papers analyzed in the present study.

Almost half (48.8%) of the papers analyzed in the present study were published in just four journals – the Journal of Cleaner Production, Water Science and Technology, Water, and

Resources, Conservation and Recycling (Figure 4), while 13 journals each provided only one paper. None of the papers included in the analyses were published prior to 1999, with the number of studies published per year peaking at six, in 2018 and 2021 (Figure 5). There is a clear tendency for the number of papers published annually to increase over time, except for a marked decline in 2019–2020, which was likely related to the COVID-19 pandemic. The apparent reduction in the number of publications in 2022 is likely related to the fact that the literature search only covered the first half of this year.

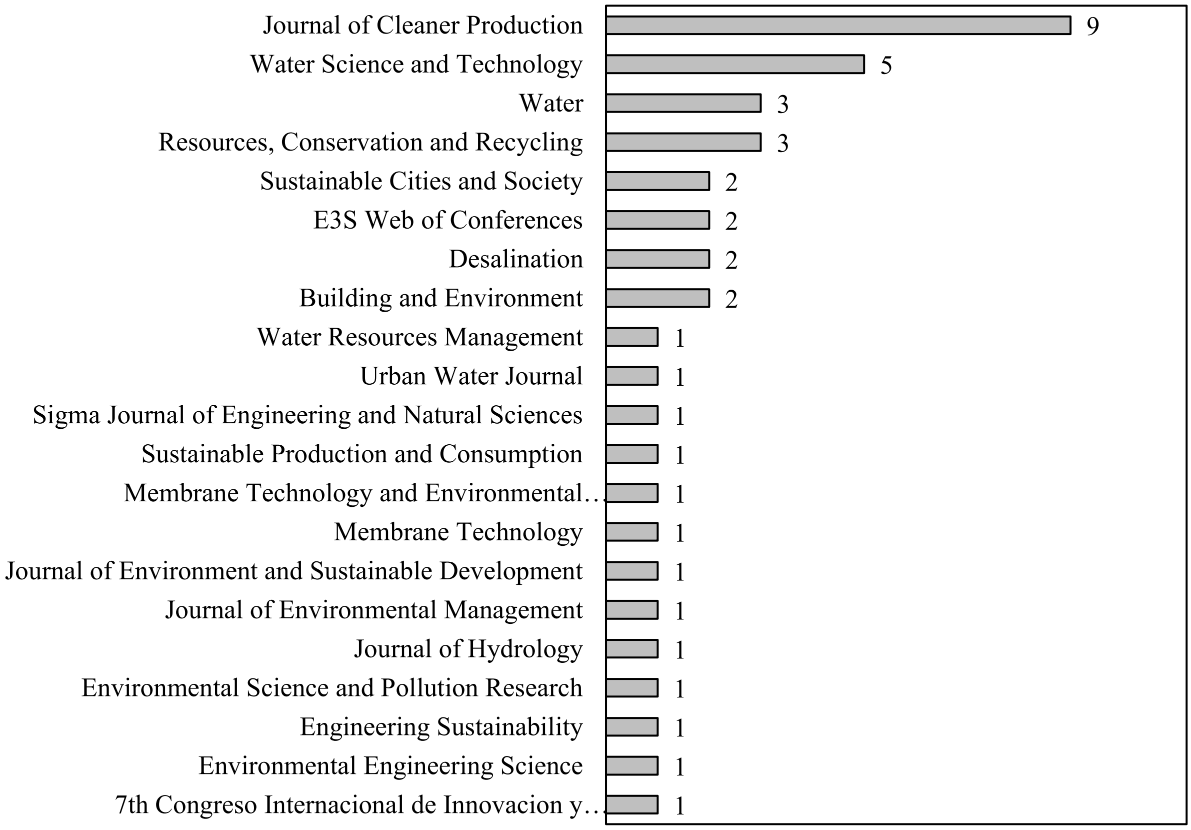

Figure 4. The number of studies published per journal, considering the 41 papers analyzed in the present study.

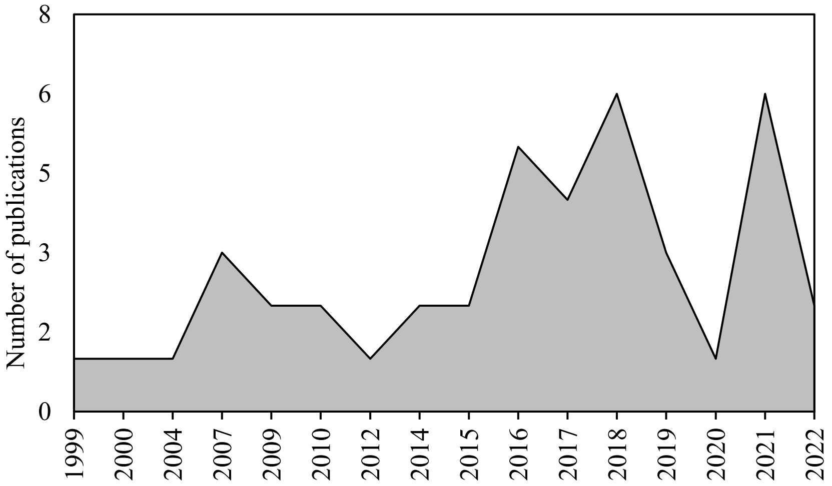

Figure 5. The number of studies published per year, considering the 41 papers analyzed in the present study.

The keywords provided in the metadata of the databases were analyzed using StArt, with their relative frequencies being plotted in a word cloud (Figure 6), in which the font size is proportional to the frequency of the word in the 41 papers selected for analysis. The most frequent keyword was “water supply”, which appeared in 32 (78.0%) papers, followed by “rain”, in 30 (73.2%) papers, and “wastewater reclamation”, which appeared in 24 (58.5%) of the selected papers. Other prominent keywords included “rainwater”, found in 21 (51.2%) papers, “rainwater harvesting” and “recycling”, both recorded in 13 (31.7%) papers, “greywater”, in 12 (29.3%), “Brazil", in 11 (26.8%), “housing”, in nine (22.0%), and “greywater recycling” and “cost benefit analysis”, both recorded in eight (19.5%) of the selected papers.

Figura 6. Word cloud of the keywords provided by the authors of the 41 papers analyzed in the present study.

3.2. Configurations and limitations of the combined RWH-GWR systems observed in the studies

This section is arranged into two parts. The first part presents and discusses the characteristics and configurations of the combined RWH-GWR systems presented in the studies, and the principal trends found in the literature. The second part addresses the limitations found in the studies that need to be resolved in future research.

3.2.1. Primary configurations and research topics addressed in the studies

The primary configurations of the combined RWH-GWR systems were compiled from the 41 papers selected for analysis in the present study (Supplementary Material, Table S1). Based on the Köppen-Geiger climate classification categories of the study locations (Supplementary Material, Table S1), precipitation levels do not vary significantly over the course of the year at most sites, except Cranbrook, Australia (semi-arid), Athens, Greece (dry summers), Nagpur, India (drier summers), Ankara, Turkey (dry summers), and Cusco, Peru (dry winters).

An extensive dry season can impact the performance of a RWH system by reducing water savings and leaving the storage tanks empty for long periods, which can greatly increase the lag on the payback for the initial investment. In this scenario, it is essential to combine RWH with GWR to avoid stagnation during the dry season or other periods of water scarcity.

A shortage of water supplies affects not only the city itself, but also economic activities such as agriculture and industry, resulting in increased production costs of many goods (Hertel and Liu, 2019; IPCC, 2021). Low levels in reservoirs also affect the production and costs of hydroelectric power (Hertel and Liu, 2019).

In all cases, the RWH and GWR systems were deployed in either households or commercial buildings, including offices and educational facilities (Supplementary Material, Table S1), while none of the studies focused on industrial installations or agricultural infrastructure. Some activities may demand large amounts of water, which exceed the production capacity of the RWH and GWR systems. In this context, the improvement of water management in urban areas will depend on the large-scale development of decentralized systems to relieve the demand for water from mains supplies and avoid the risk of overloading the central system (Sapkota et al., 2015).

The characteristics of the RWH and GWR systems described in the papers analyzed in the present study, including the collection, treatment, storage, and final use of the recycled water, are discussed in more detail below.

3.2.1.1. Water collection

In the case of commercial buildings (schools, offices, and universities), greywater is collected primarily from sinks, and at some sites, in showers, but never from washing machines or laundries (Supplementary Material, Table S1). At residential sites, regardless of whether the study focused on a single home or a group of houses, grey water was collected most frequently from showers/bathtubs, sinks, and washing machines. Greywater was collected from kitchen sinks in only three cases (Aybuğa and Işildar, 2017; Chen et al., 2021; Zhang et al., 2010). Greywater from kitchen sinks and dishwashers tends to contain more organic contaminants, and is commonly referred to as “dark grey water” (Leong et al., 2017).

Rainwater was harvested exclusively from roofs, with areas ranging from 20 m^2 to 100,000 m^2 (Supplementary Material, Table S1), except in the study of López Zavala et al. (2016), where water was collected from a catchment area that included roofs, terraces, and parking lots, with a total area of 65,768.75 m^2. It is important to note here that López Zavala et al. (2016) used the term “stormwater” which is distinguished from “rainwater” (which is collected exclusively from rooftops) due to inclusion of the runoff from all the permeable and impermeable surfaces within the drainage system (Sapkota et al., 2015).

3.2.1.2. Water treatment

A number of different treatment methods are available for greywater and rainwater, depending on their intended reuse. The process typically involves the removal of physical, chemical, and biological contaminants to render the water adequate for a specific application. In general physical treatment is a preliminary step prior to chemical or biological processing, or is used as an enhancement phase prior to disinfection. Physical processing helps to eliminate suspended solids, which improves the efficacy of subsequent disinfection treatments (Leong et al., 2017).

The physical treatments for rainwater found in the papers analyzed here were first flush, ultrafiltration, reverse osmosis, fiber media and metal membrane filters, self-cleaning leaf filters, sedimentation tanks, grease and oil traps (in stormwater drainage systems), and coarse, multimedia, deep bed, granular activated carbon, and sand filters. In the case of greywater, most of these treatments were used, except first flush and self-cleaning and deep bed filters, with the further addition of slow sand and tile fragment filters, as well as aeration systems (with compressors).

In the case of biological treatments, only artificial wetlands were reported for the treatment of rainwater (Birks et al., 2004; Smith et al., 2000), whereas a number of different treatments were used for greywater, including wetlands, aerated and crushed tire biofilters, membrane bioreactors, natural soil treatment systems, GW bioMembranes (DeHoust GWM), as well as other, unspecified processes. While more effective for the removal of organic material, procedures that involve aeration or hydraulic pressure can demand large, relatively costly amounts of energy and water for backwashing (Castleton et al., 2014). In this case, it is important to assess not only the efficiency of a procedure for the removal of contaminants, but also its environmental and financial feasibility, when selecting treatments.

The most common type of chemical treatment of both rainwater and greywater was chemical disinfection using chlorine (Cl_2), followed by the use of ozone (O_3). Physical disinfection by ultraviolet radiation (UV) was also applied in some studies, although there were no reports of chemical coagulation. It is important to note that neither the O_3 nor the UV techniques leave chemical residues in the water, which can be problematic for storage due to the potential growth of microorganisms. Only two studies referred to the use of residual chlorine following disinfection by UV (Zanni et al., 2019) and O_3 (Chen et al., 2021).

3.2.1.3. Water storage

The principal model used for the sizing of the storage tanks of the combined RWH-GWR systems was the mass balance model (Supplementary Material, Table S2), which is based on estimates of inflow and outflow rates, together with the stored water levels and the final volume of the tank. In addition, algorithmic models such as the "yield before spillage" (YBS) and "yield after spillage" (YAS) approaches (Jenkins et al., 1978) and software, such as Netuno, EPA SWMM, RainTANK, and AQUACYCLE, were used to estimate adequate tank size over different time scales, primarily at a daily scale, but also using weekly and historical parameters.

The modeling of RWH systems has considered data such as precipitation, the runoff coefficient (ranging from 0.8 to 0.9), catchment area, and the demand for the recovered water, whereas in GWR modeling, data on the greywater discharge and demand for specific end uses are the most typical parameters. Most of the papers selected for analysis estimated storage tank volumes separately for the RWH and GWR systems, except in some specific cases (Castleton et al., 2014; Leong et al., 2018a, 2018b; López Zavala et al., 2016).

Only two of the papers in the final dataset optimized tank size to meet the demand for water. Stang et al. (2021) used the Brent method to maximize energy savings in each household, whereas Zhang et al. (2021) modeled hourly data from a 5-year rainfall series with a mixed integer-linear programming model to optimize both tank size and the operation of the system.

Total water demand ranged from 61 to 234 liters per capita per day (Supplementary Material, Table S2). Some studies estimated total water consumption from data provided by residents, who measured water consumption by volumetrically at each hydraulic fixture (Coutinho Rosa and Ghisi, 2020; Ghisi and Ferreira, 2007; Ghisi and Mengotti de Oliveira, 2007; Marinoski et al., 2018; Marinoski and Ghisi, 2019; Vieira and Ghisi, 2016). These authors provided an estimate of mean daily water consumption of 147.4 liters per person. On average in residential systems, showers account for 29% of total water consumption, while toilet flushes consume 23%, kitchen sinks, 18%, clothes washing, 19%, and washbasins, 6%, with the remaining 5% being dedicated to other uses. The collection of water from showers, washbasins, and washing machines by GWR systems thus represents 54% of the wastewater generated by a household, while the demand for reuse in toilet flushes and clothes washing accounts for approximately 42% of the total consumption.

A number of studies (Birks et al., 2004; Chen et al., 2022, 2021; Dixon et al., 1999; Leong et al., 2017; Markovič, 2018; Ryan et al., 2009; Wanjiru and Xia, 2018) indicated that, as shown by Liu et al. (2010), the size of a raw greywater storage tank should be adjusted to ensure that storage time does not normally exceed 24 hours. This is because malodorous compounds and microorganisms tend to increase over time in greywater stored for periods longer than 24 hours, in particular, microorganisms, which will increase exponentially.

Chen et al. (2021) reported that both raw and treated greywater were discharged into the sewage system after 24 hours in a study in Japan, following the recommendation of Liu et al. (2010). However, this disposal was deemed unnecessary due to the use of an advanced treatment system, which included a membrane bioreactor, aeration system, and ozone disinfection, with extra levels of residual chlorine. It is interesting to note here that discharge fees are charged for effluent disposal in Japan. This indicates the need to review the 24-hour storage limit, given that it may generate unnecessary waste and increase the operating costs of a GWR system, which may compromise critically both its economic and environmental benefits.

3.2.1.4. The end use of the recovered water

The end use of the recovered water, whether rainwater, greywater or a mixture of the two, was identified in all the 41 papers analyzed in the present study (Supplementary Material, Table S1). Toilet flushing was the principal destination for recovered water, especially greywater. Reuse in urinal flushes was limited to commercial buildings. Clothes washing was the most widely accepted application for rainwater, while the irrigation of gardens was the second most frequent use for all three types of recovered water. External uses, including car and pet washing, and floor cleaning, were the third most common reuse option for rainwater. While all three types of water were appropriate for floor cleaning, only rainwater was used for fire control, cooling towers, and dishwashing.

It is interesting to note that none of the studies cited end uses that require potable water, which is likely due to the more straightforward monitoring and lower initial investment costs of RWH and GWR systems, which recover water for non-potable purposes. This reflects the need for frequent analyses to ensure safe consumption and, in particular, the application of public health protocols and water potability standards.

3.2.1.5. Research topics

The final dataset includes papers that focused on a number of different aspects of water management (Figure 7). More than half (25) of the papers analyzed the potential of the systems for saving water, while 13 analyzed the costs, nine evaluated means to reduce water wastage, eight discussed water quality, six discussed Life Cycle Costs (LCC), four were based on Life Cycle Assessment (LCA), while three studies each examined water treatment for reuse and the social acceptance of water management practises.

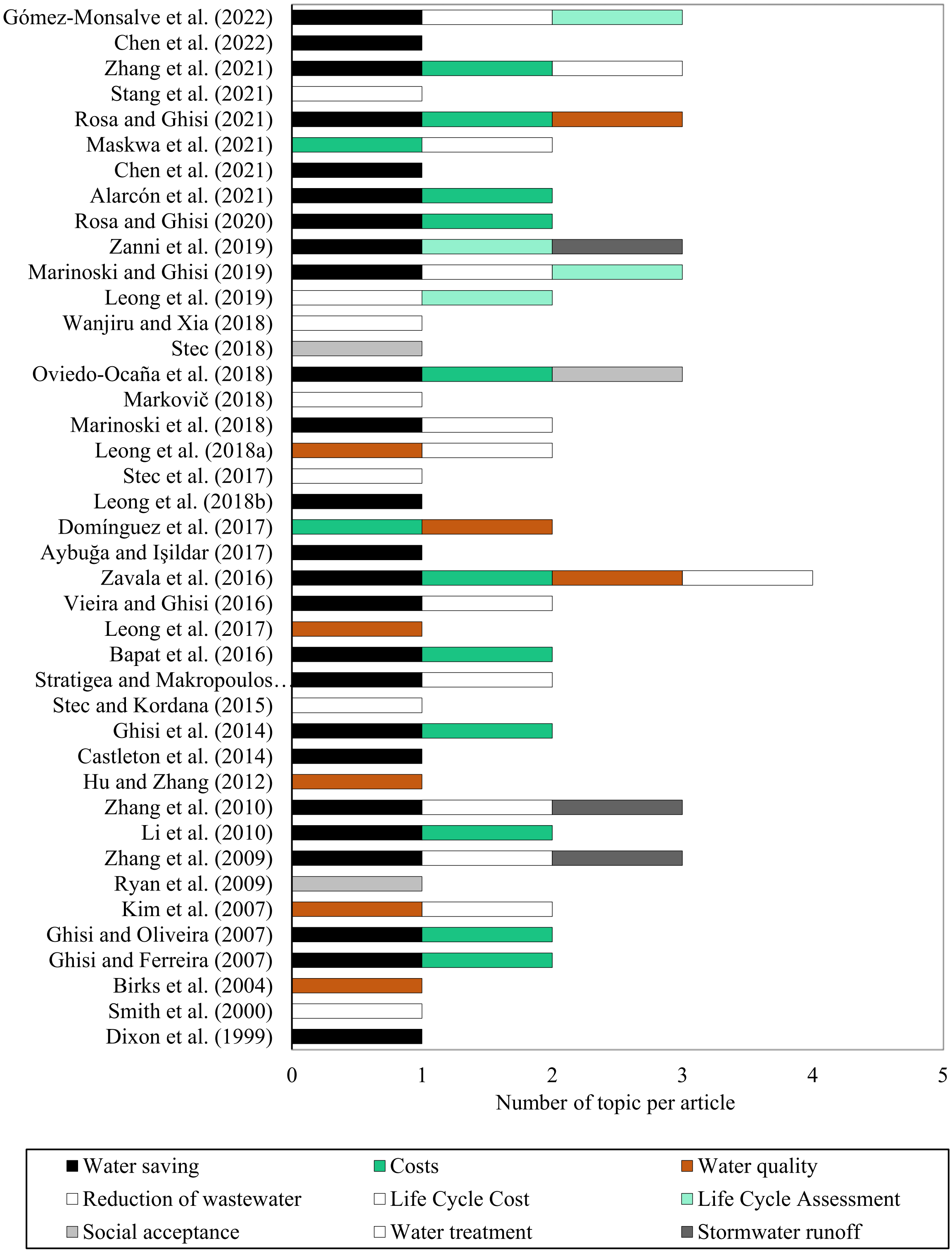

Figure 7. Principal research topics considered in the evaluation of RWH and GWR systems in the 41 papers analyzed in the present study.

Over the past 23 years, saving water and cost analyses have been the topics investigated most extensively, while LCC and LCA are relatively new topics, with the first studies appearing in 2015 (LCC) and 2019 (LCA). By contrast, the least popular topics were water treatment, stormwater runoff, and the social acceptance of water management practises.

Studies of the savings of drinking water provided by RWH and GWR systems have been conducted for both the individual and combined systems, although the data show that the hybrid systems provide the greatest water savings (Dixon et al., 1999; Li et al., 2010; Ghisi and Oliveira, 2007; Ghisi and Ferreira, 2007; Ghisi et al., 2014; López Zavala et al., 2016). However, Castleton et al. (2014) obtained atypical results in terms of water savings because the cleaning of the rapid filter used to treat the water from both RWH and GWR systems consumed more recovered water than the systems were able to produce. This meant that the process had to be supplemented with potable water from the mains.

When considering the reduction of wastewater by GWR, the concentration of contaminants in brown wastewater is a cause for concern, given that it can have negative impacts on the system, including blockages, odors, and corrosion (Marleni et al., 2012; Sapkota et al., 2015). However, Guven and Tanik (2020) have suggest that the concentrated content of this water favors anaerobic treatment, with the potential for the generation of electricity through the recovery of methane gas. These findings further emphasize the need for a more systematic evaluation of the impacts of GWR on the collection and treatment of conventional wastewater.

The RWH systems can reduce stormwater runoff, which can relieve pressure on the drainage network and reduce the risk of flooding, depending on the number of systems implanted in the watershed (Xu et al., 2022). However, few studies have evaluated the potential of RWH for the mitigation of urban flooding, especially at a large scale.

The cost analysis studies focus mainly on the economic potential of combined rainwater and greywater recovery systems, while neglecting the assessment of environmental feasibility. Meanwhile, the LCA and LCC studies have concentrated primarily on construction and operation phases, comparing RWH and GWR systems with the mains water supply. This comparison is relatively redundant, given that the main purpose of using these decentralized systems is precisely to complement the mains water supply, not to replace it.

Overall, these studies have many deficiencies in both their environmental and economic aspects, primarily because current GWR and RWH systems depend on considerable inputs, including high levels of energy consumption, abundant quantities of chemicals, and continuous maintenance (Razman et al., 2022). Given this, one research priority is clearly the need to develop more efficient and sustainable systems that minimize environmental impacts and reduce operational costs. In addition, LCA and LCC studies should focus on the entire life cycle of the system, from the extraction of the raw materials to the final disposal of the residues. This would allow for a more accurate evaluation of the environmental and economic performance of the systems, as well as the identification of potential pathways for improvement.

Studies of water quality adopted strict potability standards, even for non-potable uses, which implies that the current standards were not developed specifically for water reuse. In addition, while the treatment technologies used in the reuse studies are similar to those used in the production of potable water, few studies assessed the effectiveness of these technologies. Overall, there is still strong social resistance to the reuse of rainwater and greywater, even after adequate disinfection, which is probably due to the widespread use of potable water for all domestic needs, regardless of whether potability is actually necessary (Stec, 2018; Ryan et al., 2009).

In this case, the lack of public awareness of the risks of water scarcity and other environmental issues remains a major obstacle throughout much of the world. This is reflected in the scarcity of studies of the social acceptance of RWH and GWR systems, whereas health risks and financial returns are predominant topics. This implies that ensuring effective changes in beliefs and habits is one of, if not the principal obstacle that needs to be overcome to ensure the expansion of decentralized water reuse technologies in urban areas.

3.3. Principal limitations of combined systems and perspectives for future research

First and foremost, it is important to highlight the limited scope of the sources investigated in the present study, given that the literature search was restricted to academic sources. This may not reflect the full extent of the existing knowledge on RWH and GWR systems, given the more practical nature of much of the research. A more comprehensive understanding of the state of the art of these systems would thus need to reach beyond this conventional literature, to sources such as technical reports, government documents, unpublished research, and personal communications with experts and practitioners in the field. This was beyond the scope of the present study, however, and would require a far more extensive and potentially less systematic approach. It should be recognized, therefore, that the current study represents the state of knowledge based on existing traditional literature.

In the specific case of the costs of RWH and GWR systems, for example, a number of the studies cited here examined this specific aspect of the technology, and consistently identified the storage tank as the most expensive component (Oviedo-Ocaña et al. 2018; Zhang et al. 2021). One potential solution is to combine the storage of the two types of water in a single tank, which reduces both overall investment and operational costs, and avoids having the rainwater tank lie idle during periods when rainfall is scarce or inexistent, an increasingly common scenario in many regions around the world (Toreti et al. 2022).

In most cases, especially in the case of RWH systems, the tank design considered only costs and the potential savings (Ghisi & Ferreira 2007; Ghisi & Mengotti de Oliveira 2007; Ghisi et al. 2014; Vieira & Ghisi 2016). Clearly, this perspective should be revised to consider objectives such as the minimization of the volumes of rainfall runoff, which will be important to reduce the risk of floods in urban areas.

It will also be essential to consider the future impacts of climate change on combined system projects, even though this may result in increased initial costs, due to the need to increase tank volume and the harvesting area. One potential solution for this problem is the modular expansion of projects proposed by Loiola et al. (2019), which permits the spreading of construction costs over time, while improving the capacity of the system to adapt to extreme climate scenarios, such as droughts and floods.

In the context of water scarcity, it is important to note that agriculture alone accounts for 72% of the global consumption of freshwater, whereas urban consumption accounts for only 12% of the total, and industrial applications, 16% (FAO 2021). It would thus be essential to design combined RWH-GWR systems considering not only water security, but also food security, including irrigation for small-scale and sustainable food production, especially in urban areas. The use of rainwater and greywater for irrigation can reduce the need for fertilizers (Chojnacka et al. 2020), while pathogenic microorganisms can be eliminated by disinfection.

Liu et al. (2010) alerted that the quality of greywater may degrade after being stored for more than 24 h. Given this, it will be necessary to investigate more systematically both the environmental conditions that favor the growth of microorganisms and the most effective disinfection processes, in order to avoid wasting recovered greywater and ensure the financial viability of GWR systems.

The advanced treatment technologies commonly used in RWH and GWR projects, such as MBR, BFA, filtering and metallic membranes, despite being highly effective for the removal of contaminants, have a short lifespan and high energy consumption, which can reduce both the environmental and economic performance of the systems. It is thus necessary to design systems that reduce energy consumption, inputs, and the need for module replacement, principally by using technologies that rely on ecosystem services, i.e., nature-based solutions (NbSs), such as artificial wetlands and biofilters. A number of studies have shown that these technologies are capable of removing all types of contaminant, ranging from suspended solids to emerging micro-pollutants, such as pesticides and antibiotics, from artificial wetlands (Datta et al. 2013; Vymazal & Březinová 2015).

The parameters evaluated most frequently in the papers analyzed in the present study included potable water savings and costs, as well as LCA and LCC assessments. However, any evaluation of the environmental performance and economic viability of combined systems will be redundant if these systems are not rethought to become more sustainable. In particular, it will be necessary to reconcile water treatment technologies with renewable sources of electricity, such as solar panels and anaerobic biodigesters.

One important aspect that has been widely overlooked is social acceptance, which will be essential to ensure scientific dissemination and the creation of a platform for dialogue among researchers, policy makers, companies, and communities. Despite the importance of the economic and hygiene aspects, it will be essential to approach social acceptance in an innovative and comprehensive manner, considering all the different facets and challenges of this fundamental problem.

It will also be important to evaluate systematically the implications of the large-scale introduction of RWH and GWR systems in urban watersheds. In particular, it will be important to determine how to evaluate the effects of these systems on the hydrological cycle, in particular in the urban context. While some studies have employed smart water meters (Castleton et al. 2014; Vieira & Ghisi 2016; Markovič 2018), real-time measurement is still incipient in this field of research. The more accurate measurement of water input and output in these systems will provide more reliable data for realistic hydrological modeling.

These combined systems should also be designed bearing the objectives of the United Nations' Sustainable Development Goals (SDGs) of the 2030 Agenda in mind. These goals include water savings, the reduction of urban runoff and carbon emissions, nutrient cycling, food production, and energy savings. Given this, it is important to have precise data on the different variables to best evaluate the benefits provided by these systems and their implications for urban resilience.

Although there have been important advances in the research on RWH and GWR systems, the general lack of regulations or standards, and the weak integration of systems remain a major challenge. In particular, it will be vital to provide insights that favor the regulation of decentralized systems and the water quality standards for reuse, which will ensure the development of more efficient and sustainable water management practices.

Overall, then, close collaboration between researchers, professionals, and stakeholders will be crucial to strengthen the fundamental principles addressed in the present review. The understanding of RWH and GWR systems would also benefit greatly from the implementation of case studies and the collection of empirical data, which would be recommended for future studies. Practical, real-world evidence can provide important input, and complement ongoing scientific research, providing a more comprehensive overview of the state of the art of the field, while addressing the knowledge gaps identified here in an effective and reliable manner.

4. CONCLUSIONS

The present study was based on a systematic review of the scientific literature on combined rainwater harvesting and greywater reuse systems. The selection of studies based on the search criteria resulted in the identification of 41 papers that were relevant to the objectives of the present study. In general, these systems have been implemented primarily at residential and commercial scales, as a complement domains water supplies. The recovered water was used for toilet flushing, floor cleaning, and garden irrigation. Rainwater was treated using simple procedures for the removal of suspended solids and pathogenic microorganisms, while the greywater treatment also included the removal of organic matter. Tank sizing was based on mass balance models using historical rainfall data and estimates of water demand. The topics covered most frequently in the papers analyzed here were potable water savings and cost analyses.

Finally, the present study highlights the need to invest in innovative technologies that satisfy demands for sustainability, such as the use of renewable sources of energy, recyclable materials, and the reduction of environmental impacts. In order to ensure the performance of these systems in both environmental and economic terms, it will be necessary to better evaluate the interaction between this technology and contextual factors, including the local climate, the availability of resources, and existing infrastructure. It will also be important take social acceptance into consideration and the potential for the involvement of the local community. These factors will be essential for the successful implementation of the systems and their long-term sustainability, especially in the context of ongoing shifts in climate. Overall, the quest for effective, decentralized water management solutions in urban areas will be essential to guarantee adequate supplies of water in the future.

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CHAPTER II – OPERATIONAL ADJUSTMENTS TO IMPROVE WATER QUALITY IN AN INTEGRATED RESIDENTIAL RAINWATER AND GREYWATER RECYCLING SYSTEM

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Abstract

The present study assessed the operational performance of an Integrated Rainwater and Graywater Recycling System (IRGRS) installed in a one-family residence in the town of Rio Verde, central Brazil. This system combines reduced costs with ease of operation, including the harvesting of rainwater, pre-treatment of graywater in an artificial wetland, continuous aeration, cartridge filtering, and disinfection by ultraviolet radiation. It was possible to guarantee continuously the quality of the recycled water throughout the 16 months of monitoring, despite a prolonged period of drought. The recycled water satisfied the principal national and international standards for the use of non-drinking water, such as irrigation and domestic applications. The system obtained a mean saving of 41% in the consumption of mains water, and covered the total demand of the residence for non-drinking water, despite a complete lack of rain over more than six months of the study period. The results of the study showed that the long-term storage of rainwater and graywater can be viable, with adequate treatment. The study reinforced the viability of decentralized solutions for the re-use of water in urban environments, in particular, in regions vulnerable to water shortages and extreme seasonal variations in climate.

Keywords: water reuse; rainwater harvesting system; graywater reuse system; decentralized systems; UV disinfection; mains water savings; continuous aeration.

1. INTRODUCTION

The increasing scarcity of water resources in urban areas, together with the need to adapt to climate change through sustainable practises, are driving the widespread adoption of decentralized systems for Rainwater Harvesting (RWH) and Graywater Reuse (GWR) in residential buildings (Semaan et al., 2020; Stang et al., 2021; Gómez-Monsalve et al., 2022; Shao and Xu, 2023). These systems complement conventional water supplies, and contribute to a reduction in the demand for mains water, thereby attenuating the impacts of droughts, and mitigating the risks of flooding during the seasonal rains (Tamagnone et al., 2020; Tao et al., 2023; Sharma et al., 2023). These systems can thus be considered to be decentralized solutions capable of reinforcing the resilience of urban water supplies in the context of ongoing climate change (IPCC, 2021; Muñoz-Pizza et al., 2023).

Despite the advances in the research and application of this technology, many important lacunas persist. In particular, very few studies have focused on the durability of graywater that has been stored over long periods (Liu et al., 2010; Chen et al., 2021), in particular, in regions that are subject to prolonged droughts, when graywater becomes the only source for the system. In addition, very few studies have assessed the quality of the rainwater and graywater stored in hybrid reservoirs following an integrated process of treatment (Rodrigues et al., 2023). The evaluation of the quality of the water stored under these conditions is crucial for the understanding of their efficiency across varying seasonal conditions, especially in terms of microbiological control and organoleptic features, which are essential to ensure the acceptability and viability of the water for non-drinking uses.

A number of previous studies have reported on a variety of different types of technology that has been developed for the reuse of water, which have combined biological processes, such as membrane filters with Membrane Bioreactors, or MBRs (Zhang et al., 2010; Atanasova et al., 2017; Cecconet et al., 2019). A number of studies have also described conventional systems that employ activated sludge followed by ultrafiltration (Verrecht et al., 2010), as well as Bubble-Aerated MBRs, or BA-MBRs (Timmer, Vaz et al., 2025). However, these systems consume large amounts of energy, not only for aeration, but also for cleaning the membranes (Lee et al., 2013; Meng et al., 2017; Jiang et al., 2019).

While some studies and reports have focused on graywater treatment systems that employ aeration followed by filtration, as well as disinfection by ultraviolet radiation, there have been few efforts to integrate these three steps in a single system (Teh et al., 2015; Kabiri et al., 2021; Awasthi et al., 2024). The use of cartridge filters in this context has also been investigated only very rarely (Rodrigues et al., 2023). This approach, which is based on a combination of low-cost and accessible technology, intends to mitigate the effects of the water that decants during storage, to prevent the proliferation of microorganisms and stabilize the quality of the water over time, thereby guaranteeing the safety of its non-drinking use, even when there is no rain.

In addition to the quality of the water, it is fundamental to ensure that the system is capable of guaranteeing supplies of water during long periods of drought. In this context, the analysis of the hydrological balance — which considers the volume of water collected, stored, and consumed, as well as the eventual losses — supports the assessment of the system, in terms of its capacity to satisfy fully the demand of the residence for non-drinking water throughout the year. The final uses of this water include irrigation, washing external areas, floors, and vehicles, toilet flushing, and, depending on its quality, even washing clothes. Understanding the performance of these water supply systems under highly seasonal conditions will be essential for the adequate planning and replication of this technology in urban areas vulnerable to scarcity or irregular supplies of mains water.

In this context, the present study assessed the performance of an Integrated Rainwater and Graywater Recycling System (IRGRS) installed in an urban residence in central Brazil, in terms of the quality of the water supplied by the system. The analyses included the evaluation of the variation in the quality of the water over time, the efficiency of the treatment strategies, self-sufficiency during droughts, and the ideal maintenance frequency. By using empirical data collected from real conditions of use, this study aimed to contribute to the technical amelioration of these systems and the implementation of effective public policies for the decentralized management of water resources in the urban environment.

2. METHODS

The study was carried out at a single-family household with two residents, located in Rio Verde, Goiás, Central-West Brazil (17°48′38.11″ S; 50°54′52.45″ W). The property comprises a total impervious area of 311.05 m², including a roofed structure of 203.47 m², and a permeable area of 288.95 m².

The system was monitored between January, 2024, and May, 2025, a period that encompassed both the dry (May through September) and rainy seasons (October to April). The region's climate is highly seasonal, with rainy (austral) summers and dry winters, as shown by the historical series of mean monthly precipitation (mm) and temperature (°C) in the municipality of Rio Verde (Figure 1).

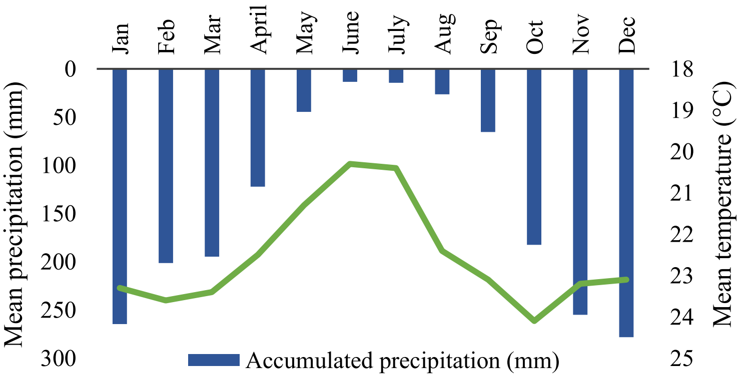

Figure 1. Historical series of mean monthly precipitation (mm) and temperatures (°C) recorded in the municipality of Rio Verde, Goiás (Brazil) between 1961 and 1990. Source: INMET (2025).

2.1. The integrated rainwater and graywater recycling system (irgrs): a case study and description

In the Rainwater and Graywater Recycling System (IRGRS) assessed here (Figure 2), the rainwater and graywater are collected separately by gravity feed, directly from their respective sources. The rainwater is collected from the roof of the residence. The graywater is produced by the showers and sinks, and the washing machine.

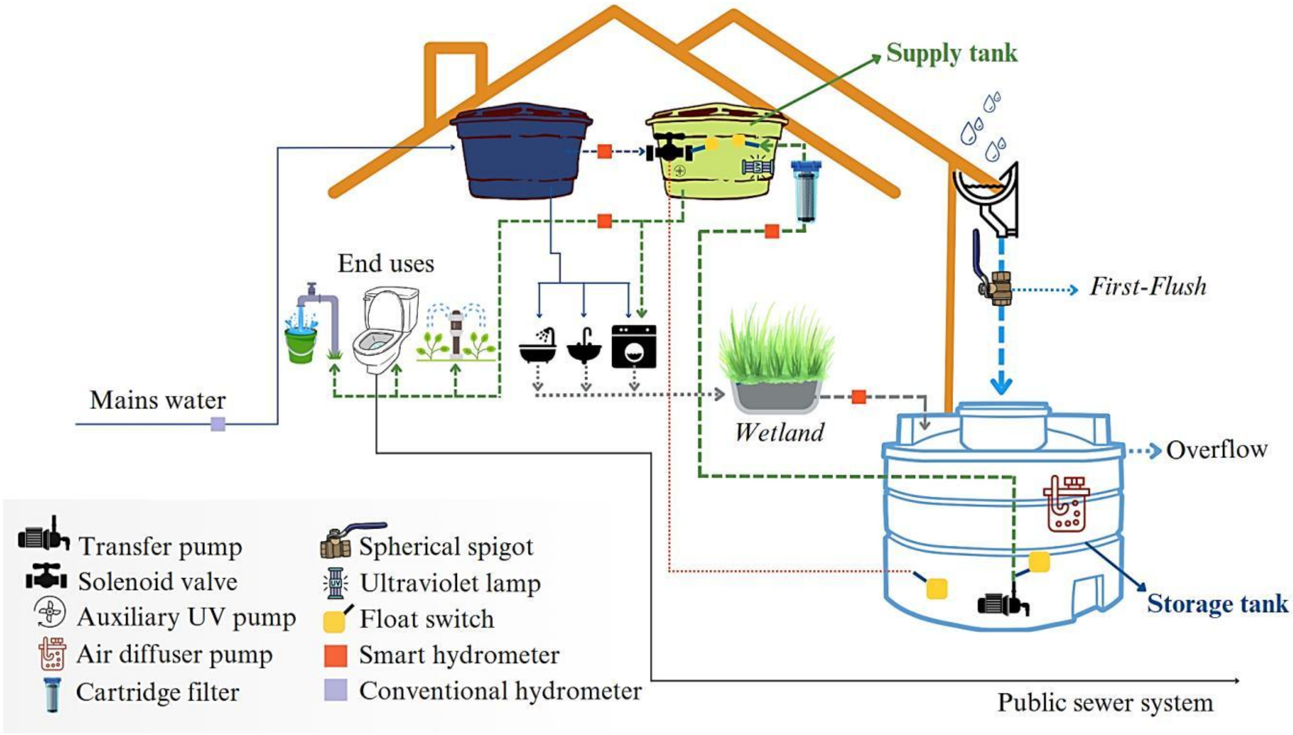

Figure 2. Diagram of the integrated rainwater/greywater recycling system (IRGRS) assessed in the present study.

The initial rainfall (first-flush) is discarded to remove atmospheric contaminants and waste from the roof, and represents a preliminary step in the treatment prior to storage. This first flush was conducted manually using a 100-mm spherical PVC spigot (Fortlev) fitted to the rainwater drainage pipe, which permitted the controlled discharge of the initial rainfall. In contrast with automatic devices — which discard systematically the first 2 mm of rainwater, even when the surface is clean — this manual system guarantees the avoidance of unnecessary losses, with the untreated water being diverted to the garden rather than being channeled into the principal reservoir tank.

The graywater is conducted simultaneously by 50-mm PVC pipes (Fortlev) to the artificial wetland, an anaerobic biological pre-treatment system. This wetland was implanted in a 2.3 m² hole in the ground, which was impermeabilized using a 1 m³ HDPE tank (Fortlev). The filter bed was filled with #1 gravel and it was planted with the macrophyte *Cyperus* *proliferus* Lam. (dwarf papyrus). The system was designed to operate with an estimated Hydraulic Detention Time (HDT) of 24 hours.

In the following step of the process, the rainwater and graywater are sent to a 5-m^3 HDPE underground collecting and storage tank (Fortlev), where the water from the two sources was mixed. The size of this tank was validated by the NETUNO 4.0 software (UFSC – labEEE, 2025). This tank is aerated continuously by a 45-W submerged pump (Sarlo Better, model SB2700), which injects atmospheric air continuously into the water at a rate of approximately 8.9 $L \cdot min^{-1} \cdot m^{-3}$. This process favors the oxygenation of the water, stimulates the action of aerobic microorganisms in the degradation of the residual organic matter, and contributes to the mitigation of residual odors, in particular that of hydrogen sulfide (H_2S), which are generated by the anaerobic conditions in the artificial wetland treatment unit.

The water in the underground reservoir tank is pumped up to the elevated 1 m^3 HDPE supply tank (Fortlev) using a submerged 450 W pump (Anauger) capable of pumping 2350 L per hour. During this process, enough pressure is generated to force the water through a fixed Polypropylene (PP) cartridge filter (Fortlev), equipped with replaceable 5-µm pore cartridges (Fortlev), or refills, which is installed in the 32 mm PVC entrance pipes (Fortlev) of the tank. This filter removes the suspended solids from the recycled water, which is necessary because the aeration process generates a small amount of biomass that must be removed to ensure the quality of the treatment.

An 11 W ultraviolet (UV) lamp (Sarlo Better, Puri Press/G23) was installed underwater in the elevated supply tank for the continuous disinfection of the treated water. An 8 W auxiliary pump (Sarlo Better, SB800A) was also installed in the supply tank to homogenize the water during the disinfection process, in order to minimize the establishment of dead zones and hydraulic short-circuits. Both these devices operate continuously, 24 hours a day, to guarantee the microbiological safety of the water up until its final use. As there is no residual chlorine in the water, continuous disinfection is necessary even for non-drinking applications, such as toilet flushing, washing floors, vehicles, and clothes, and the irrigation of vegetable plots and gardens.

The IRGR system was designed to pump water from the underground reservoir to the elevated supply tank whenever the water in this tank reaches its minimum level. This operation is automated by 15 A floating switches made of polypropylene (Anauger), which measure the maximum and minimum levels of the tanks. When the water in the underground reservoir reaches its minimum level, the electric circuit of the pump cuts off automatically.

When the level of recycled water in the underground reservoir is insufficient to meet the demand of the residence for non-drinking water, a solenoid valve (generic model) is activated automatically by a floating switch in the storage tank, which directs water from the public mains to the supply tank. The aeration and UV disinfection systems were implemented on August 25th, 2024, a number of months after the IRGR system began operating, which permitted the evaluation of the evolution of the quality of the water and the efficiency of these processes over time.

The empirical data on the volume of recycled water produced by the system were collected by hydraulic monitoring with intelligent flowmeters installed at different points within the system (Figure 2). Four pulsed output flowmeters (Unijato, wifi capable model SM-WA-HU, IEtecnologia) and an ultrasonic level sensor (wifi capable model SM-WU-HU, IEtecnologia) were used to measure the hydraulic flow and the level of the stored water, respectively. All these devices have integrated dataloggers, which transmit and store data continuously in the cloud on the Monitor IE (IEtecnologia) online platform, with the data being acquired at 1-minute intervals.

The volume of the rainwater harvested by the system was measured by an autonomous rain gage (Ciclus WRF-3S, with wifi and Bluetooth connectivity), installed on the roof of the residence. This device records the precipitation instantaneously (mm/min), providing the data necessary to estimate the amount of rainwater harvested. The data are recorded automatically and are available on the Weather Underground platform.

2.2. Hydraulic monitoring

Intelligent flowmeters were used for the hydraulic monitoring of the system, together with an automatic rain gage (Figure 1). Based on the input and output data, the hydraulic dynamics of the system were assessed through the hydrological balance, calculated using equation (1):

$$Vrainwater + Vgreywater - Vreuse - Voverflow = \frac{dh}{dt} \quad (1)$$

where,

$V_{rainwater}$ = the volume of rainwater entering the storage tank;

$V_{graywater}$ = the volume of pre-treated graywater entering the storage tank;

V_{reuse} = the volume of water pumped from the storage tank to the supply tank (equivalent to the amount of recycled water actually consumed);

$V_{overflow}$ = volume of the water discarded from the storage tank through the overflow mechanism;

$\frac{dh}{dt}$ = variation over time in the water level of the storage tank.

1. *Water savings*

The mean total consumption of water (mains + recycled) by the study residence is 170 L·inhabitant^{-1}·day^{-1}, and the water saved (reduction in the consumption of mains water) was estimated by equation (2), which provides the percentage of the consumption of mains water substituted by recycled water. This parameter provides a measure of the performance of the IRGR system in terms of the reduction of the dependence of the residence on the public mains supply.

$$Water\ saving\ (\%) = \frac{Vreuse\ x\ 100}{Vpot\acute{a}vel + Vreuse} \quad (2)$$

where,

Water saving (%) = the percentage saving of mains water consumption;

V_{reuse} = total volume of recycled water consumed by the residence from the supply tank (m^3), and

V_{mains} = volume of tap water (in m^3) consumed by the residence, supplied by the public mains.

2.3. Monitoring the quality of the water

A total of eight different parameters were measured to determine the quality of the recycled water leaving the supply tank (Table 1), with measurements being taken on either a daily or a weekly basis. The procedures and analytical instruments used to evaluate the quality of the recycled water followed the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF, 2012). The analyses were run in the Laboratory of Sanitation and the Environment of the Rio Verde campus of the Goiás Federal Institute, Brazil.

The mean values recorded for the water quality parameters (physicochemical and microbiological variables) were compared between periods using Student's t, with a 5% ($p < 0.05$) level of significance. The data were compared between rainy and dry seasons, and also between the periods prior to and following the implementation of the aeration and UV radiation systems. Prior to this analysis, the homogeneity of the variances between groups was assessed using an F test, to determine whether the t test should be applied for samples with homoscedastic or heteroscedastic variances. All calculations were run in Microsoft Excel.

Table 1. Water quality parameters and the laboratory procedures used to analyze the samples collected during the present study.

Parameter	Method	Equipment	Frequency
Turbidity	Nephelometric (2130 B)	Turbidimeter (Akso, TU430)	Daily
Electrical Conductivity	Conductivity meter (2510 B)	Multiparameter apparatus (Akso, AK88)	Daily
pH	Potenciometric (4500 B)	Multiparameter apparatus (Akso, AK88)	Daily
Temperature	Direct measurement	Multiparameter apparatus (Akso, AK88)	Daily
Odor	Sensorial assessment	Qualitative sensorial analysis (olfactive)	Daily
Thermotolerant coliforms	Multiple Tubes Technique (9221 B)	—	Weekly
Surfactants	Jurado et al. (2006), simplified	Spectrophotometry with methylene blue	Weekly
Chemical Oxygen Demand (COD)	Closed Reflux, Colorimetric (5220D)	Reator de digare (Hach, DRB200); Spectrophotometer (Kasvi, K37-UV-VIS)	Weekly

3. RESULTS AND DISCUSSION

This section presents the principal findings of the monitoring of the IRGR system evaluated in this case study. This analysis focused on the operational efficiency of the system, principally in terms of the quality and safety of the water produced by the system for non-drinking uses in an urban context.

3.1. Hydraulic performance of the system

The hydraulic performance of the system was assessed through the hydrological balance of the underground storage tank. For this, the daily, weekly, and monthly input of rainwater and graywater was analyzed, together with the output of recycled water (pumped to the elevated supply tank for final use), losses (overflow), and the volume of stored water (see Figures 3 and 4).

The daily input and output of water from the storage tank over the 490 days of the study period is shown in Figure 3. The amount of rainwater harvested varied considerably among the days, and principally between the well-defined dry and rainy seasons. During the rainy season months, more than 12 m^3 of rain was harvested on some days, whereas there was no measurable rainfall during much of the dry season. During the latter period, in fact, the storage tank depended exclusively on the input of graywater. Given this, overflow events occurred only during the days when rainfall peaked, reflecting the limited storage capacity of the reservoir (4.49 m^3 of effective storage capacity) during intense rains. By contrast, the amount of recycled water used by the residence remained relatively stable over time (Figure 3), reflecting the virtually constant demand of the residence for non-drinking water.

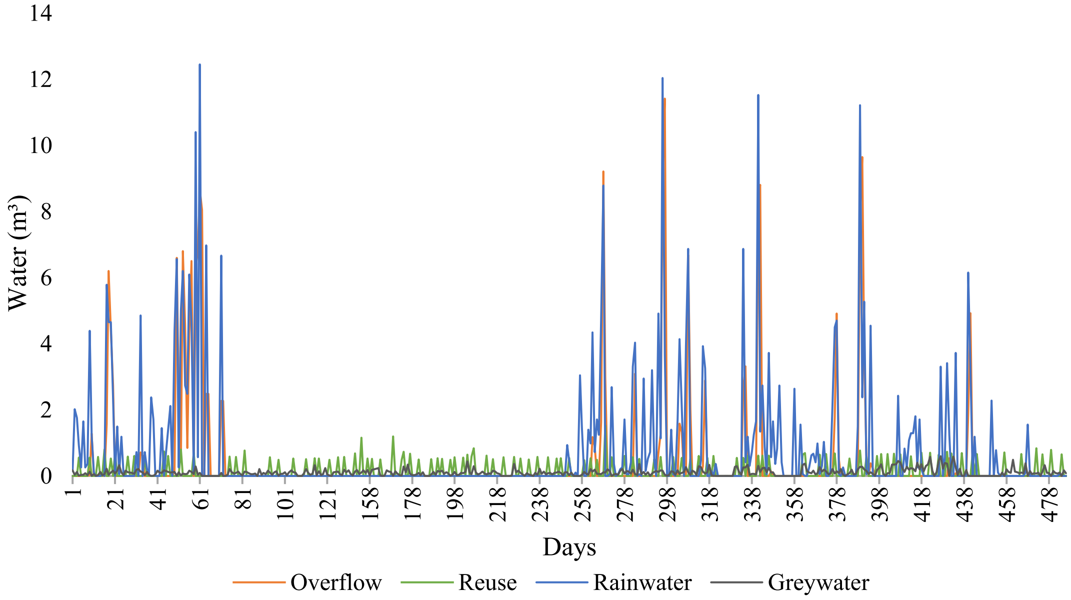

Figure 3. Daily input and output in the water recycling system installed at the study residence in Rio Verde, Goiás, central Brazil, over the 490 days of the study period (January, 2024, through May, 2025).

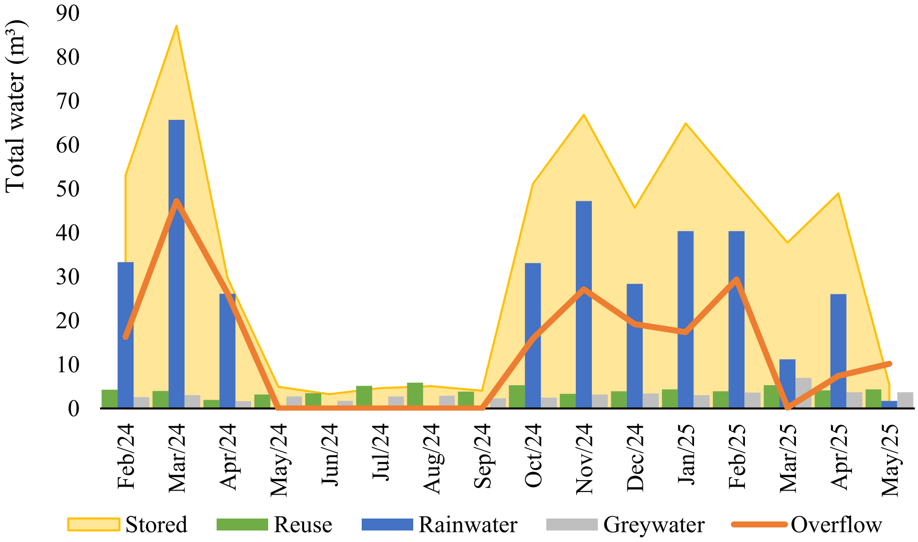

Figure 4. Total amount of water (rainwater + graywater) stored, reused, and overflowed each month by the water recycling system installed at the study residence in Rio Verde, Goiás, central Brazil, between February 2024 and May 2025.

The monthly pattern (Figure 4) highlighted the clear seasonal variation observed between February, 2024, and May, 2025. The highest levels of input and overflow were recorded during the rainiest months, in particular, in March, 2024, when a total of more than 80 m³ of water were fed into the reservoir. However, a large proportion of this water was discarded through overflow, given the low, but constant demand for reuse, which remained unaltered, even during the periods of increased rainfall harvest. This divergence reflects the under-exploitation of the system during the rainy season.

On the other hand, the under-exploitation of the recycled water observed in the study revealed a considerable potential for the amplification of the distribution of the stored water, which could be used for other purposes, such as the irrigation of gardens and urban vegetable plots, and the maintenance of swimming pools. This intensification of reuse would permit the more controlled output of the reservoir, optimizing this storage capacity during periods of intense rainfall. In addition to increasing the operational efficiency of the system, this strategy would mitigate overflow and reduce the pressure on the urban drainage system, while also reinforcing the potential role of the system as a complementary solution for flood control in urban areas (Xu et al., 2022).

On the other hand, the reduced variation in the amount of water destined for reuse contributed to the satisfactory performance of the system in terms of fulfilling the demand for water of the study residence during the dry season. Even after a continuous six-month period with no rainfall (between April 1st and October 8th, 2024), the solenoid valve — which was installed to activate the supply of mains water whenever the water stored in the reservoir tank reaches a critical level — was not switched on at any time. This means that the system was fully able to satisfy the demand of the study residence for non-drinking water, even during periods of prolonged drought. Although the residence had only two occupants during the study period, larger households—such as multi-family dwellings—would likely produce proportionally greater volumes of graywater, thereby demonstrating the system's potential scalability for larger populations.

Given the principal limitations and operational perspectives discussed in previous analyses, it would seem reasonable to recommend the implementation of integrated rainwater and graywater recycling systems in steps, through the modular expansion of the storage tank, as a practical way of adapting the system to extreme climate scenarios, such as droughts and flooding (Rodrigues et al., 2023). Even so, the results of the present study indicate that it would be advisable to evaluate the potential for the reuse of the water collected during the rainy season before amplifying the operational capacity of the reservoir, given that the consumption of the recycled water may fall well short of the amount harvested. From this perspective, the principal priority should be the amplification of water reuse, rather than a simple increase in storage capacity.

3.2. Savings of mains water

The total consumption of water (including the mains) of the study residence, the non-drinking use of recycled water, and savings all varied considerably across the different months of the study period (Figure 5), between February, 2024, and May, 2025. The average total consumption over the 16-month monitoring period was approximately 10.1 m³ per month, of which around 4.1 m³ were supplied by recycled water and 6.0 m³ by potable water. This resulted in an average reduction of approximately 41% in mains water usage.

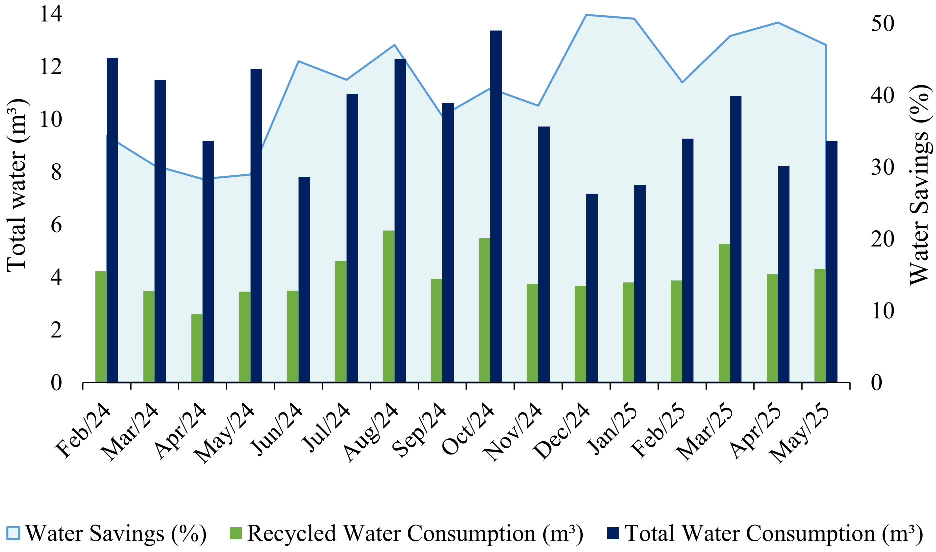

Figure 5. Total consumption of water, consumption of recycled water, and the mean savings of mains water (%) recorded each month at the study residence in Rio Verde, Goiás, central Brazil, between February, 2024, and May, 2025.

Between 28% and 51% of the consumption of mains water was saved per month over the study period as a whole. The greatest savings were recorded in November, 2024 and January and March, 2025, due to the increased availability of rainwater. These figures are consistent with the findings of many previous studies. For example, Ghisi and Ferreira (2007) and Ghisi and Oliveira (2007) recorded savings of between 35% and 42% in combined Rainwater Harvesting (RWH) and Graywater Reuse (GWR) systems. Vieira and Ghisi (2016) reported a reduction of 43% in the demand for mains water through the use of RWH systems, and 24% by GWR. Gómez-Monsalve et al. (2022) obtained savings of 42.5%, while Rosa and Ghisi (2021) recorded 38% in integrated RWH and GWR systems. All these percentages are similar to those recorded in the present study.

Some studies have recorded much less efficient values, however, reflecting the determining influence of the local context, the scale of the components of the system, and water reuse patterns. Zhang et al. (2021) obtained savings of only 28.3% from integrated RWH and

GWR systems, while Zhang et al. (2009) reported values of only 6.9–10.4% for RWH from roofs of 600–900 m², although this reduced performance was attributed to the region's low precipitation levels, with an average annual rainfall of only 774.3 mm and a relatively uniform monthly average of approximately 64.5 mm throughout the year.

Similarly, Ghisi and Oliveira (2007) verified that, while rainwater harvesting satisfied 34.6% of the demand for water at their study site, while the graywater system, operating independently, had an efficiency pf only 28%, possibly because of a lack of adequate storage or other barriers to treatment and reuse over the long term. In a second study, Ghisi et al. (2014) reported an extremely low level of efficiency, of only 3.05%, for a GWR system, under conditions of infrastructure and use that were not adapted adequately to a scheme of continuous reuse.

One particularly relevant example here is the study of Castleton et al. (2014), which recorded a negative balance (of between -8.5% and -10.0%) for integrated systems, with a hybrid storage tank similar to that assessed in the present study. The problem in this case was the amount of water required for the backwashing of the “rapid-multimedia filter” used in the treatment was greater than that recuperated by the system, which meant that an input of mains water was necessary to complement the supply necessary for the backwashing and supplying the toilet flushes of the commercial building monitored in the study. The contrasts observed between the different studies emphasize the fact that efficiency of reuse systems may vary considerably, depending on factors such as the compatibility between supply and demand, the technical design of the system, storage capacity and treatment, and the consumer profile.

The amount of recycled water used by the study residence for different non-drinking purposes each month also varied considerably over the course of the study period (Figure 6). Between May and October 2024, most of the recycled water was used for irrigation and washing floors and other surfaces, in particular in August and September, when consumption peaked at up to 4 m³ per month. This increase in consumption coincides with the peak of the dry season, when the low relative humidity, combined with atmospheric pollution, favored the accumulation of dust, including in the internal areas of the residence. This intensified the demand for washing and the irrigation of vegetables plots and gardens.

The consumer profile changed noticeably from January 2025 onward, with a major shift in the use of the recycled water for flushing toilets and washing clothes. This change occurred, in part, due to the fact the recycled water began to be used for washing clothes, which was not the case prior to January 2025, but also because the increase in the rains reduced the amount of dust in the environment, which led to a reduction in the demand for water for washing surfaces and irrigation. In March, 2025, for example, more than 4 m³ of the recycled water was applied to the flushing of toilets and washing clothes, the largest amount of water used for these purposes in a single month during the present study period.

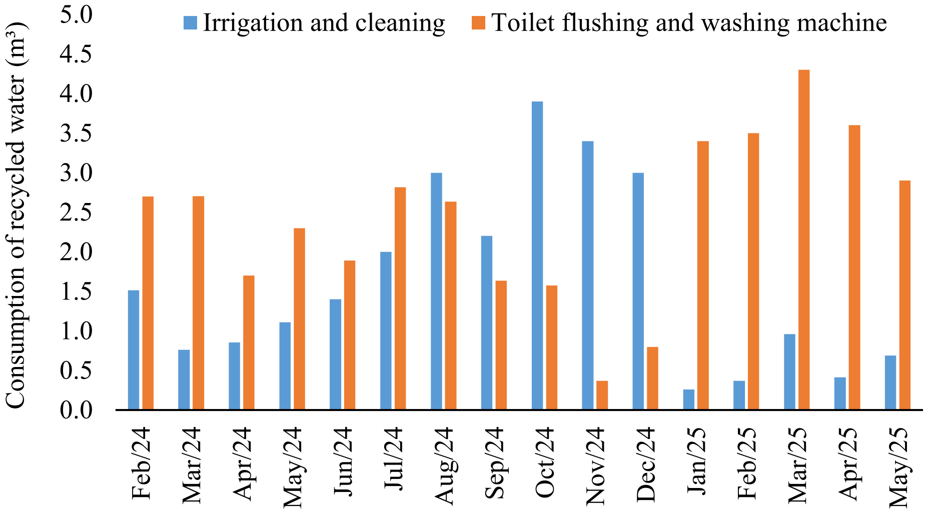

Figure 6. Monthly consumption of recycled water used for non-drinking purposes in the study residence in Rio Verde, central Brazil, between February 2024 and May 2025.

Ultimately, the monthly savings of up to 50% observed in the consumption of mains water reinforce the effectiveness of the integrated rainwater and graywater recycling system as a means of satisfying continuously the demands of the study residence for non-drinking water, such as irrigation, toilet flushing, and washing floors and clothes. This uninterrupted replacement of mains water with recycled water reflects the efficiency of the system, even during prolonged periods of drought.

3.3. Assessment of the quality of the recycled water

Four parameters of water quality – turbidity, electrical conductivity, pH, and temperature – were monitored daily during the 490 days of the study period (Figures 7 and 8) between January 28th 2024 and May 31st 2025. The 2024 dry season was defined as the period between study days 79 and 254 (April 11th–October 7th), based on the absence of rainfall throughout this interval. The 2025 dry season began on May 10th, based on the criterion of at least 15 consecutive days with daily precipitation below 1 mm and a monthly accumulated precipitation of less than 30 mm. The aeration and disinfection of the recycled water by UV radiation were implemented during the dry season, on day 211 (August 25th 2024).

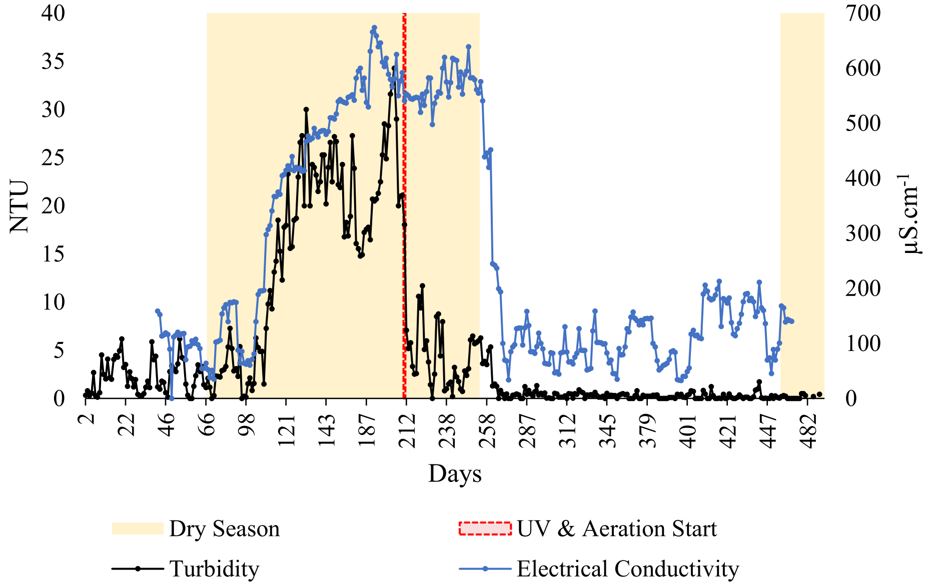

Figure 7. Daily variation in the turbidity (NTU) and electrical conductivity (µS.cm^{-1}) recorded over the 490 days of the study period in Rio Verde, Goiás, central Brazil.

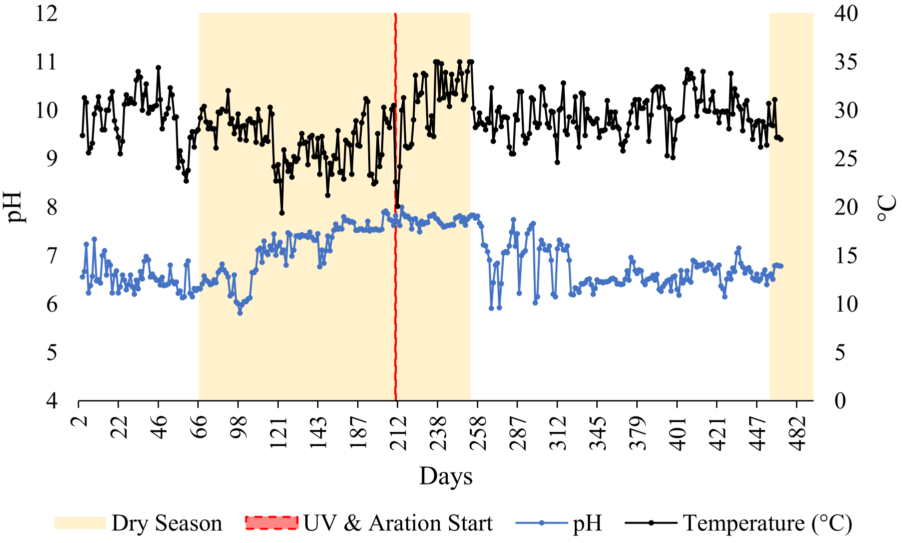

Figure 8. Daily variation in the pH and temperature (C°) recorded over the 490 days of the study period in Rio Verde, Goiás, central Brazil.

Three other parameters – Chemical Oxygen Demand (COD) and the concentrations of surfactants and thermotolorant coliforms – were monitored weekly (Figures 9 and 10). This resulted in data for a total of 70 weeks of monitoring between January 28th 2024 and May 31st 2025.

During the rainy season, which corresponded to the first 66 days of monitoring – January 29th through April 2nd – turbidity remained consistently below 5 NTU, which is below the threshold established for mains water by Brazilian Health Ministry ordinance GM/MS 888/2021 (Brasil, 2021). This maintenance of low levels of turbidity can be attributed to the dilution of the graywater by the rains, which also likely contributed to the low density of thermotolerant coliforms (<20 NTU.100 mL^{-1}) and the lack of perceptible odors recorded during this period.

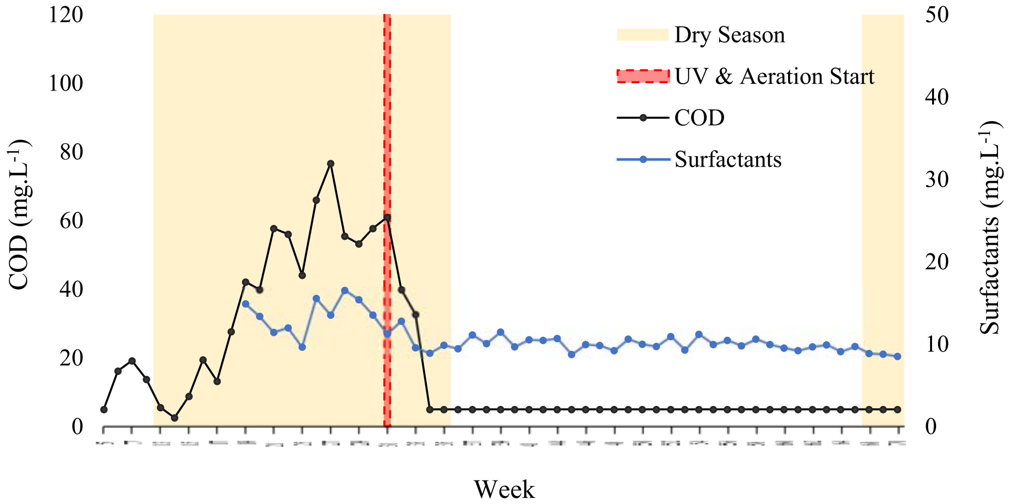

Figure 9. Weekly variation in the Chemical Oxygen Demand (COD) and concentration of surfactants (mg.L-1) recorded over the 70 weeks of the study period in Rio Verde, Goiás, central Brazil.

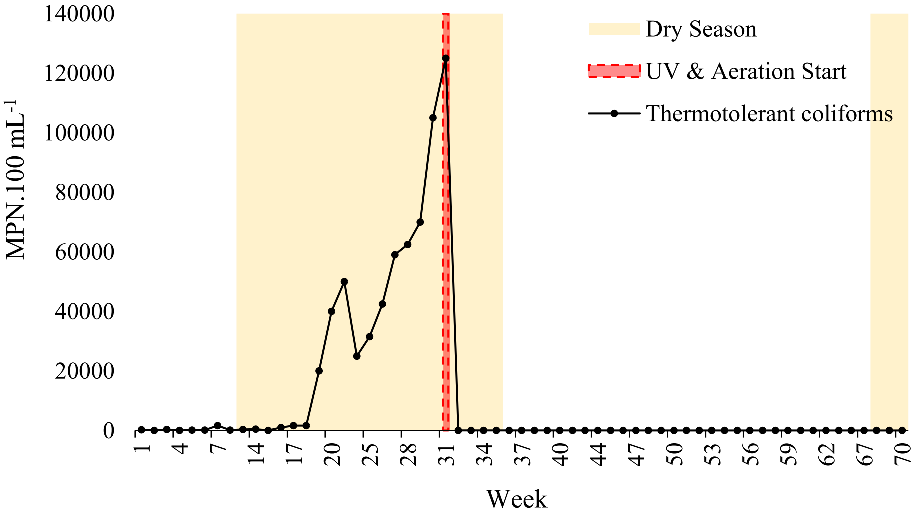

Figure 10. Weekly variation in the thermotolerant coliform concentration (MPN.mL-1) recorded over the 70 weeks of the study period in Rio Verde, Goiás, central Brazil.

The turbidity levels recorded in previous studies also vary considerably, according to the origin of the water and the level of treatment. Leong et al. (2016) reported the highest values for rainwater (RW), with turbidity of between 3 and 1,349 NTU, whereas Hu and Zhang (2012) recorded turbidity of 0.2–304 NTU for RW and 60–240 NTU for graywater (GW). Intermediate values were recorded by Kim et al. (2007), with turbidity of 1–42 NTU (RW) and 29–185 NTU (GW), and by Zavala et al. (2016), with 1–24 NTU (RW) and 130–167 NTU (GW). By contrast, studies that involved more intense levels of treatment, such as those of Domínguez et al. (2017) and Rosa and Ghisi (2021), have reported residual turbidity of less than 2 NTU, reflecting an even greater stability in the quality of the water.

With the transition to the dry season, and the lack of rain, however, there was a progressive deterioration in the quality of the water. The lack of rainwater favored an increase in the concentration of organic matter, which was reflected in a marked increase in turbidity, COD, and the density of thermotolerant coliforms, which exceeded $\log_{10}$ 5.08 MPN·100 mL^{-1} (approximately 120,000 MPN·100 mL^{-1}). Between days 143 and 210, unpleasant odors were also consistently recorded in the toilet flush. Leong et al. (2018) reported comparable levels, with concentrations ranging from $\log_{10}$ 3.70 to 4.78 CFU·100 mL^{-1} (5,000–60,000 CFU·100 mL^{-1}) in untreated rainwater, while Domínguez et al. (2017) observed values up to $\log_{10}$ 5.19 CFU·100 mL^{-1} (155,000 CFU·100 mL^{-1}) in graywater.

The pH remained in the neutral zone, between 6 and 8, throughout the monitoring period, which is compatible with the parameters established by Brazilian Health Ministry ordinance GM/MS 888/2021 for water destined for human consumption. This further reinforces the adequate quality of the recycled water produced here for less restricted non-drinking purposes, such as irrigation and toilet flushing. The temperature of the water remained below 35°C, even during the hottest months (October and November), which is also with the limits recommended for mains water in Brazil (Brasil, 2021).

The constant neutrality of the pH (6–8) is consistent with the findings of previous studies (e.g., Kim et al., 2007; Leong et al., 2016). Similarly, the electrical conductivity, which peaked at 650 $\mu\text{S.cm}^{-1}$ during the dry season, remained within the range of values reported by Hu and Zhang (2012) and Kim et al. (2007). In the case of COD, the values recorded in the present study did not exceed 76.7 mg.L^{-1}, which is compatible with the range of values recorded by Hu and Zhang (2012), i.e., 106–675 mg.L^{-1}, and by Leong et al. (2016) – 76–645 mg.L^{-1}. In the present study, however, the COD was reduced to below 5 mg.L^{-1} following the introduction of UV disinfection and aeration, with results that were much more effective than those reported in most previous studies.

From day 211 onward, continuous aeration of the storage tank and disinfection by ultraviolet (UV) radiation were both added to the system, as shown in the graphs (dashed red line). These modifications resulted in a significant improvement in the quality of the water. Turbidity was reduced by 88%, and remained below 0.5 NTU for most of the rest of the study period, for example, while the Chemical Oxygen Demand (COD) decreased by 81%, and remained below the detection limit of the method (<5 mg·L^{-1}) during the final months of monitoring. Similarly, thermotolerant coliform concentrations were reduced by 4.07 log, and remained at 0–2 NTU.100 mL^{-1}, which is also close to or below the limit of quantification of the method. This is also consistent with the criteria of the World Health Organization, which require a reduction of 3–4 log for restricted irrigation and ≤ 1,000 *E. coli*/100 mL for unrestricted irrigation (WHO, 2006).

By contrast, physicochemical parameters such as the pH, electrical conductivity, and surfactant concentrations did not vary significantly following the implantation of the new processing systems (aeration + UV disinfection). This indicates that aeration and UV radiation, while effective for the removal of organic matter and microorganisms, do not have any direct effect on the dissolved ions or surfactant compounds present in the graywater. Electrical conductivity remained high during the dry season, however, decreasing only after the onset of the rains (day 255, week 36).

While highly significant differences were found between the rainy and dry seasons in the levels of all the physicochemical microbiological variables in the period prior to the implementation of the aeration and UV disinfection systems (Table 2), the scenario was less clear following the implementation of these systems. While all the variables except temperature presented the same seasonal trend (increasing from the rainy to the dry season), the differences were only significant for turbidity, pH, and conductivity.

The implantation of the aeration and UV disinfection systems had a clear impact on the values recorded for all the variables except the pH of the water, which was invariably higher during the dry season, but was not affected by the installation of the purification systems (Table 2). Temperature increased significantly after the installation of the systems; however, this rise was primarily attributed to seasonal climatic conditions rather than to the treatment technologies themselves. The elevated values reflected the high ambient air temperatures typically observed during the late dry season, particularly in the transition to spring (August–October), when rainfall is still scarce and temperatures remain elevated.

Despite this difference, the turbidity of the recycled water decreased highly significantly ($p = 0.000$) following the implantation of the systems, with similar, but less significant ($p < 0.003$) declines being recorded in conductivity, COD, and, in particular, thermotolerant coliform concentrations, which decreased from a mean of more than 30,000 MPN.100 mL^{-1} prior to the implantation of the systems, to only 7 MPN.100 mL^{-1} after the systems became operational.

Table 2. Statistical comparisons of the mean values recorded for the physicochemical and microbiological variables during the different seasons and periods of the present study in Rio Verde, Goiás, central Brazil. Significant values of t are highlighted in bold script. ND = Not Determined.

		Mean±SD of the values (n = number of days) recorded for the variable:						
Comparison	**Period**	**Turbidity (NTU)**	**pH**	**Temp. (°C)**	**Electrical conductivity (μS.cm^{-1})**	**Thermotolerant coliforms (MPN.100 mL^{-1})**	**COD (mg.L^{-1})**	**Surfactants (mg.L^{-1})**
Rainy *vs.* Dry season (before implantation of UV disinfection & aeration systems)	**Rainy (Jan–Apr 2024)**	2.26 ± 1.41 (n=60)	6.53 ± 0.21 (n=58)	29.20 ± 2.16 (n=58)	99.97 ± 23.05 (n=58)	243.45±256.92 (n=10)	13.51±4.26 (n=3)	ND
	Dry (Apr–Aug 2024)	15.64±8.22 (n=98)	7.11±0.45 (n=98)	26.77±2.13 (n=98)	391.41±168.92 (n=98)	31,365.47±26,792.23 (n=13)	40.44±20.68 (n=14)	13.39±1.84 (n=8)
	***t* (*p*)**	**-15.70 (<0.001)**	**-10.90 (<0.001)**	**6.83 (<0.001)**	**-16.80 (<0.001)**	**-4.188 (0.001)**	**-4.452 (<0.001)**	**ND**
Rainy *vs.* Dry season (after implantation of UV disinfection & aeration systems)	**Rainy (Sep 2024–Apr 2025)**	0.48±0.47 (n=149)	6.72±0.33 (n=149)	29.47±1.58 (n=149)	126.80±56.92 (n=149)	0.72±1.05 (n=28)	6.93±3.73 (n=28)	10.05±0.53 (n=28)
	Dry (Aug–Oct 2024 & May 2025)	3.12 ± 2.64 (n=42)	7.58 ± 0.25 (n=42)	30.48±2.75 (n=42)	509.57 ± 100.99 (n=42)	7.00 ± 5.43 (n=6)	13.94 ± 12.77 (n=6)	10.01 ± 0.63 (n=6)
	***t* (*p*)**	**-6.452 (<0.001)**	**-18.257 (<0.001)**	-2.277 (0.069)	**-23.532 (<0.001)**	-2.822 (0.083)	-1.333 (0.289)	0.145 (0.722)
Before *vs.* After (implantation of UV disinfection & aeration systems)	**Before (Combined Average of Rainy and Dry Seasons)**	10.56±9.22 (n=158)	6.89±0.47 (n=156)	27.67±2.44 (n=156)	283.05±194.98 (n=156)	17,834.16±25,306.36 (n=23)	33.78±21.23 (n=17)	ND
	After (Combined Average of Rainy and Dry Seasons)	1.06±1.70 (n=191)	6.91±0.48 (n=191)	29.69±1.94 (n=191)	210.97±178.18 (n=191)	1.83±3.36 (n=34)	8.39±7.89 (n=34)	10.04±0.56 (n=34)
	***t* (*p*)**	**12.778 (0.000)**	-0.289 (0.773)	**-8.401 (0.000)**	**3.601 (<0.001)**	**3.379 (0.003)**	**5.161 (<0.001)**	**ND**

While it was not possible to determine the effects of the implantation of the systems on the concentrations of surfactants, due to the reduced sample size (Table 2), the evidence that there was no significant difference between seasons following the implantation ($p = 0.722$) indicates that the systems were relatively ineffective at controlling the content of these persistent pollutants. Otherwise, the evidence indicates emphatically that the aeration and UV disinfection guaranteed the microbiological quality of the water and effectively reduced the concentrations of suspended and dissolved solids, including fractions of the biodegradable organic matter.

The operational norms for the reuse of water in both agriculture (irrigation) and urban applications vary somewhat among the different national and international regulating bodies (Table 3). In comparison with these guidelines, the results of the present study indicate that the water produced by the IRGR system assessed here was of adequate quality for most types of reuse.

Table 3. Guidelines for the physicochemical and microbiological parameters of recycled water destined for agriculture and urban use, as defined by selected public authorities in Brazil and other countries, worldwide.

Parameter	**South African Guidelines**	**EPA 2004 - Water Reuse Guidelines**	**ISO 16075-2 (2015)**	**ABNT NBR 15527 (2007)**	**ABNT NBR 16783 (2019)**	**Other Guidelines (agricultural water reuse)**
Turbidity (NTU)	0–1 no risk; >5 risks begin	2 (avg)–5 (max), more than three states	2 (avg)–5 (max), food crops eaten raw	<2.0; for less restrictive uses <5	<5	British Columbia Unrestricted: 2
pH	6.0–9.0 ideal range, no health or taste effects	6.5–7.5 Reclaimed Water	–	6.0–8.0	6.0–9.0	AGWR (2008): 6.2–9.8
Temperature (°C)	>30°C promotes microbial growth	>30°C favors microbial growth	–	–	–	–
Odor	1–5 TON; no or slightly perceptible odor	Reclaimed water should be odorless	–	–	–	–
Electrical Conductivity (μS.cm^{-1})	–	–	–	–	–	AGWR (2008): 200–2900
Organic Load Indicators (mg.L^{-1})	DOC < 5, estimated COD < 10	COD < 50 Reclaimed Water	BOD5: 5–10 (food crops eaten raw)	–	BOD5 <20	Israel: COD <100 NS
Thermotolerant Coliforms (MPN.100mL^{-1})	>10 MPN/100 mL (infectious dose)	2.2–23 (food crops); 23–240 (restricted urban reuse)	10–100 (food crops raw); 200–1000 (processed); 1000–10,000 (non-food)	Absent in 100 mL	≤200 *E. coli*	British Columbia: Restricted (weekly) 200; Unrestricted (daily) 2.2
Surfactants (mg.L^{-1})	–	<1 Reclaimed Water	–	–	–	Italy: 0.5; AGWR (2008) (anionic): 0.2

Note: NS = Not Specified; DOC = Dissolved Organic Carbon; COD = Chemical Oxygen Demand; BOD$_5$ = Biochemical Oxygen Demand (5 days).

In particular, the turbidity of less than 0.5 NTU, achieved following the implementation of the aeration and UV disinfection systems, was well within the range of values recommended by ISO 16075-2 (2015), i.e., 2–5 NTU for the irrigation of food crops, EPA (2004) – 2–5 NTU for both urban and agricultural reuse, and the South African Guidelines, which indicate risks only above 5 NTU. In addition, the turbidity recorded in the present study was well below the threshold recommended by Brazilian norms, ABNT NBR 15527 (2007), for the non-drinking reuse of rainwater collected from urban roofs, and NBR 16783 (2019), for the alternative sources of non-drinking water in residential buildings, which in both cases is 5 NTU.

The pH, which remained between 6.0 and 8.0 throughout the monitoring period, was within the guidelines established by all the authorities mentioned above, including Brazilian standards (6.0–9.0), the EPA (6.5–7.5) and the ISO. Following the implementation of the aeration and UV disinfection, the thermotolerant coliform concentrations (0–2 NTU.100 mL^{-1}) were below the strictest thresholds established by the regulatory agencies, such as the EPA, which defines a threshold of 2.2 NTU.100 mL^{-1} for unrestricted daily reuse, ISO that defines a threshold of 10–100 NTU.100 mL^{-1} for the irrigation of vegetable crops destined for raw consumption, and the South African guidelines, which indicate sanitary risks at concentrations of above 10 NTU.100 mL^{-1}. At less than 5 $mg.L^{-1}$, the Chemical Oxygen Demand (COD) recorded here is also well below the EPA threshold of 50 $mg.L^{-1}$, and is compatible with the 5-day Biological Oxygen Demand (BOD_5) established by ISO (5–10 $mg.L^{-1}$) and ABNT NBR 16783 ($BOD_5 < 20$ $mg.L^{-1}$).

Despite being somewhat higher during the dry season (up to 650 $\mu S.cm^{-1}$), the electrical conductivity recorded in the present study was also well within the range established by guidelines such as the Australian AGWR (200–2900 $\mu S.cm^{-1}$). By contrast, surfactants, even though they are not regulated by Brazilian norms, had a mean concentration of approximately 10 $mg.L^{-1}$, which is well above the most restrictive international guidelines, such as those of Italy (0.5 $mg.L^{-1}$) or the AGWR (0.2 $mg.L^{-1}$ for anionic surfactants). This indicates the need for complementary treatments when the water is destined for more sensitive purposes.

Based on the findings of Krishnan et al. (2016), the reduced potential of the system for the removal of surfactants (26%) may be related to the resistance of these compounds to conventional treatments. As they are recalcitrant compounds, surfactants tend to persist in the water, given that processes such as simple UV radiation do not provoke their mineralization. For greater efficiency, these authors recommended Advanced Oxidation Processes (POAs), como UV/H_2O_2 or ozone/UV, which produce hydroxyl radicals capable of degrading these compounds more completely.

The application of aeration at a rate of 8.9 $L.min^{-1}.m^{-3}$ resulted in the complete elimination of the odors perceived by the inhabitants of the residence, indicating the oxidation of the volatile and sulfurated compounds accumulated in the water ever since its pre-treatment in the artificial wetland, which is a predominantly anaerobic environment. The aeration rate used here is approximately 14 times higher than that used by Zee et al. (2007), who applied aeration at a rate of 0.49–0.63 $L.min^{-1}.m^{-3}$, which likely accounts for the more effective removal of odors recorded in the present study. These authors clarify that, under these conditions, the sulfate is converted predominantly into elementary sulfur and polysulfates, with a reduced formation of sulfate, especially when the pH was close to neutral, as verified in the system assessed here. Similarly, Samarathunga and Rathnasiri (2023) observed that micro-aeration favors the stable formation of elementary sulfur and the mitigation of volatile sulfurous compounds.

The results of the present study were also consistent with the standards for drinking water established by Brazilian Health Ministry ordinance GM/MS 888/2021, including the absence of thermotolerant coliforms per 100 mL, pH of between 6.0 and 9.5, and the lack of undesirable odors (Brasil, 2021). However, the formal regulations for the reuse of water in Brazil are still limited and fragmented. The parameters of the Brazilian Association for Technical Norms (ABNT), while relevant here, lack any effective articulation with a nationwide public policy. The lack of any specific federal legislation also contributes to the heterogeneity of norms among the country's states, only a few of which have complementary regulations for the reuse of water (Moura et al., 2020).

While it does not have any regulatory power, the Guidelines for the Reuse of Water in Brazil (DRAB), established by the Brazilian Institute for Water Reuse and published in 2025, represent an important technical advance, by proposing an approach based on the assessment of microbiological risks. These guidelines establish standards of quality differentiated according to the proposed use (e.g., urban, agricultural or industrial) and recommend the implantation of monitoring plans proportional to the scale of the system and its level of risk.

Based on this approach, the quality of the recycled water produced in the present study was compatible with the requisites of Brazilian National Environment Council (CONAMA) resolution number 357/2005, which establishes standards for the classification of bodies of water for human use. The water analyzed here satisfied the standards of the special class, which demands a complete lack or naturally minimal concentration of thermotolerant coliforms, typical of preserved environments, such as integrally protected conservation areas, which can be used for public mains supplies with only simple disinfection. During the rainy season, in fact, even without any additional UV disinfection, the recycled water satisfied the criteria of class 1 ($\leq$200 $NTU.100\ mL^{-1}$ in 80% of the monthly samples), which is compatible with its general use with simple disinfection, for primary contact recreation, the protection of aquatic life, the irrigation of vegetables consumed raw, aquaculture, and fisheries (BRASIL, 2005).

One other preoccupation, which is widely accepted in the technical literature, and was initiated by Liu et al. (2010), is the recommendation that graywater that has been stored for more than 24 hours should be discarded due to the risk of exponential bacterial growth. This recommendation has been adopted in a number of subsequent studies, such as those of Leong et al. (2017), Markovič (2018), Wanjiru and Xia (2018), Chen et al. (2021), and Chen et al. (2022), and had also been supported by Dixon et al. (1999), Birks et al. (2004), and Ryan et al. (2009). However, the results of the present study indicate that it is possible to attain adequate levels of microbiological security for graywater through investment in adequate treatment, rather than discarding the water. This conclusion was supported by the fact that the water stored during the dry season was fundamental to ensure the continuous supply necessary to satisfy the demand of the study residence for non-drinking water throughout the dry season.

3.4. Operational and perceptive features

The maintenance of the supply tank (1 m^3) included the replacement of the filter cartridge and the UV lamp (Figure 11). The first intervention was conducted in week 8 (March 25th, 2024), and involved the installation of a filter cartridge with 1 µm pores and the cleaning of the tank, which was motivated by the elevated count of thermotolerant coliforms during the preceding week.

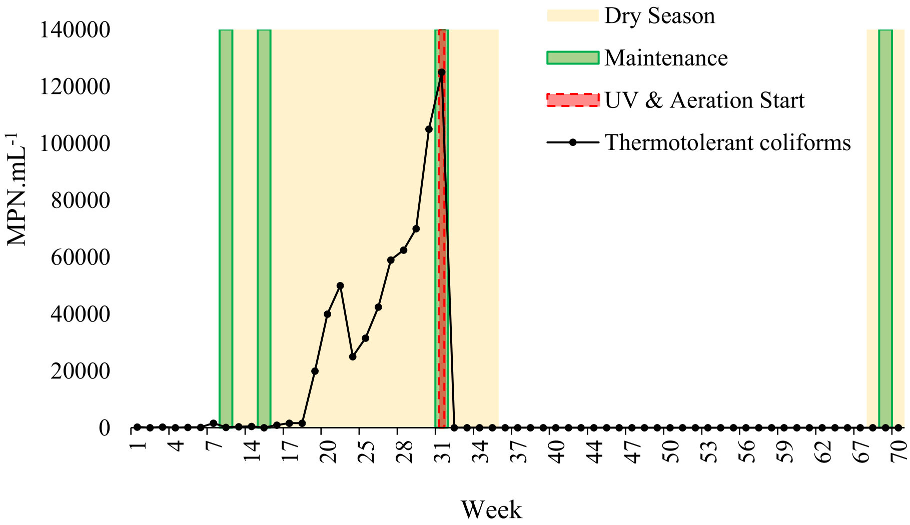

Figure 11. Comparison between the weekly variation in the thermotolorant coliform concentration (MPN.mL-1) and the timing of the periodic maintenance conducted over the 70 weeks of the study period in Rio Verde, Goiás, central Brazil.

In week 14, the transfer pump broke down, given that the pressure generated by this pump was too weak to overcome the resistance caused by the fine-pored cartridge filter, which compromised the hydraulic performance of the system. This problem was resolved by replacing the pump with a more powerful model (450 W), while the filter cartridge was replaced with a refill with 5-µm pores. The concentration of thermotolerant coliforms increased over the subsequent weeks, a scenario aggravated by the drought conditions. The abrupt reduction in the coliform count in week 24 coincided with a 15-day period during which the inhabitants of the study residence were absent, indicating the possible influence of the temporary stagnation of the water.

A comprehensive program of maintenance was conducted in week 31 (August 25th 2024), including the installation of the UV lamp and the auxiliary pump, as well as the cleaning of the storage tank and the replacement of the 5-µm filter cartridge. From this point onward, the quality of the water remained stable up until week 69 (May 20th 2025), when a slight level of contamination (23 MPN.100 mL^{-1}) was recorded, which signaled the need for new preventive maintenance. It is important to note that all these interventions were implemented based on the monitoring of the quality of the water.

Nguyen et al. (2019) demonstrated that disinfection with UV-LED lamps, associated with simple pre-treatments, is effective for the removal of organic matter, turbidity, and pathogenic microorganisms, making the water adequate for agricultural reuse. However, this study also documented the formation of incrustations on the surface of the installation, which required periodic cleaning to ensure an adequate performance. In the present study, while incrustations were observed on the surface of the underwater UV lamp, there was no loss of water quality. It seems likely that the impact of these incrustations was minimized due to the high theoretical dose of UV radiation – 250–335 mJ/cm² – accumulated over the 24 hours of continuous exposure. This estimate is based on the use of an 11 W lamp (3.3 W of UV-C at 254 nm), submerged in up to 850 L of water, with slow agitation provided by an 8 W underwater pump (United States, 2006).

The Ultraviolet Disinfection Guidance Manual published by the EPA (2006) provides guidelines on the intensity of UV radiation necessary for the inactivation of pathogenic microorganisms, which vary according to the species or type. For *E. coli* and thermotolerant coliforms, for example, UV radiation of 30–40 mJ.cm^{-2} is required, while 50–100 mJ.cm^{-2} is recommended for *Giardia*, and up to 250 mJ.cm^{-2} for *Cryptosporidium*. Given these values, the dose of UV radiation produced by the lamp used in the present study was more than adequate to neutralize most deleterious pathogens, even considering losses resulting from incrustations, hydraulic inefficiency, and the degradation of the lamp (EPA, 2006).

This manual also recommends that the UV lamps (in particular, the quartz sleeves) should be cleaned as regularly as demanded by the quality of the water and the observed performance of the lamp. A weekly or fortnightly inspection of the lamp is also recommended for systems without automatic cleaning devices, in particular when the water produced by the system is of reduced quality (United States, 2006).

The findings of the present study indicate the need for a complete cleaning of the storage tank and the replacement of the filter cartridge (5 µm) every six months, as a preventive safety measure, considering that the system operated in a satisfactory manner during 10 consecutive months without any interventions. As the UV lamp used in the present study has an estimated lifespan of approximately 8,700 hours (around one year of continuous operation), its annual replacement would be recommended to ensure the long-term continuity of the disinfection process.

4. CONCLUSIONS

The present study demonstrated that, when designed adequately and monitored and operated effectively, integrated rainwater and graywater recycling systems (IRGRS) are capable of guaranteeing the microbiological security and physicochemical stability of the recycled water, even under conditions of prolonged drought. This was achieved through a combination of (i) the pre-treatment of the graywater in an artificial wetland, (ii) the controlled elimination of the initial rainfall (first-flush), (iii) the continuous aeration of the water mixed in the storage tank, and (iv) cartridge filtration followed by disinfection by ultraviolet radiation in the elevated supply tank. These procedures were effective for the elimination of turbidity, organic matter, and thermotolerant coliforms, which is in accordance with the national and international standards of quality for non-drinking water. The additional advantages of the system include its low cost, reduced operational complexity, and its capacity for deployment at a residential scale.

The present study also challenges the widely-supported recommendation that graywater must be discarded after 24 hours of storage, given that it demonstrated that adequate treatment of this water is capable of preserving its microbiological quality and thereby expanding its potential uses. In addition to guaranteeing the quality of the water, the system achieved mean savings of 41% in the consumption of mains water, given its capacity to satisfy completely the demand of the study residence for non-drinking throughout the dry season without the need for any top-up from the public mains. The hydraulic analysis nevertheless revealed the under-exploitation of the water stored during the rainy season, which indicates the need for the adoption of alternative strategies, such as the expansion of the potential uses for the recycled water or the controlled discharge of the tanks, which may improve the operational efficiency of the system and reduce the number of overflow events.

Overall, then, the results of the present study reinforce the importance of integrated public policies that are based on risk evaluation, as well as the continuous monitoring of the quality of the water, to ensure the adoption of safe, effective, and sustainable decentralized reuse technology in urban areas.

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CHAPTER III – ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF AN INTEGRATED RAINWATER AND GREYWATER RECYCLING SYSTEM IN RESIDENTIAL BUILDINGS

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Abstract

The present study describes the integrated assessment of the environmental and economic performance of an Integrated Rainwater and Greywater Recycling System (IRGRS) operating in a single-family residence in central Brazil. The IRGR system was monitored over 12 months, and the analysis considered distinct operational scenarios, which varied in their demand for recycled water, the number of consumers, and the source of power (national grid *versus* solar power). The Life Cycle Assessment (LCA), which followed the ISO 14040/14044 norms and used the ReCiPe method, revealed that the operational phase is responsible for the majority of the environmental impacts, in terms of climate change and human toxicity, due to the continuous consumption of electrical power. However, the alternative scenario, with the more intensive use of recycled water and in particular for the maintenance of a swimming pool, had a better environmental performance, with a reduction of up to 50% in the impacts per functional unit. The economic analysis showed that the adoption of solar power reduced operational costs substantially, resulting in increased financial viability. The results revealed a potentially strategic role for decentralized hybrid systems in the development of urban water sustainability and the mitigation of the impacts of climate change, especially when adapted to the local context.

Keywords: Environmental benefit; Economic performance; Rainwater harvesting; Greywater reuse; Water reuse; Potable water savings; Decentralized system; Life cycle assessment.

1. INTRODUCTION

Climate change has intensified extreme weather events, such as droughts, which have aggravated water shortages and compromised the resilience of urban infrastructure around the world (Sharma et al., 2023; Daloğlu et al., 2023). According to IPCC (2022) estimates that more than 40% of the world's population has faced some level of water scarcity, and that this percentage will continue to grow over the coming decades (Gómez-Monsalve et al., 2022). In the face of these challenges, decentralized and sustainable solutions will be necessary for the long-term management of urban water resources (Shao & Xu, 2023).

Rainwater Harvesting (RWH) and Greywater Reuse (GWR) systems are alternative complements of public water supply systems, with the potential for the reduction of demand, the mitigation of pressures on drainage systems, and the conservation of natural resources (Bell, 2018; Tamagnone et al., 2020; Hdeib & Aouad, 2023). A number of recent studies have shown that the combination of these two approaches (RWH and GWR) in the same building can multiply the environmental and operational benefits significantly in comparison with the independent use of each system (Leong et al., 2019; Marinoski & Ghisi, 2019; Zanni et al., 2019).

Despite this potential, research on the effectiveness of fully-integrated RWH/GWR systems is still incipient, that is, systems that treat, store, and distribute rainwater and greywater in a single operation, known as Integrated Rainwater and Greywater Recycling Systems (IRGRS). In most cases, however, these systems have separate reservoirs and distribution networks, which may limit any potential gains in efficiency (Ghisi et al., 2014; Domínguez et al., 2017; Leong et al., 2019).

Even though the combined benefits of RWH/GWR systems are widely recognized, most of the available studies have been based on comparisons with centralized water supply and sewage disposal systems (Leong et al., 2019; Marinoski & Ghisi, 2019; Zanni et al., 2019; Gómez-Monsalve et al., 2022). These studies lack systematic analyses of the different operational scenarios and consumption profiles of recycled water.

Given this, the present study evaluates the environmental and economic performance of a residential IRGRS, assessing different scenarios of use, and considering variations in the demand for recycled water and electricity. This analysis was based on the Life Cycle Assessment (LCA) approach with comparative economic analyses, which were used to identify the exact factors determining reductions in environmental impacts and operational costs. The results of the study provide technical and policy-making guidelines for the systematic adoption of these integrated systems as a strategy for the adaptation of urban centers, which will contribute to the sustainable, long-term management of urban water systems.

2. METHODS

The following procedures were employed to evaluate the environmental performance, using Life Cycle Assessment (LCA), and the economic performance, using cost indicators, of an Integrated Rainwater and Greywater Recycling System (IRGRS) installed in a high-standard single-family residence, with a built area of 239.5 m², a permeable area of 298.3 m².

Operational data was obtained from continuous operation and monitoring of the system over a 12-month period (February 2024 to January 2025), with systematic records of the volumes of rainwater and greywater collected, pre-treated, stored, aerated, filtered, disinfected, and distributed.

Two variable factors were considered to assess system performance under different operational conditions:

1. Demand for recycled water from the system:

(i) Baseline scenario – actual demand recorded in the monitored system, derived from empirical data collected during the monitoring period. This corresponds to an average total water consumption (mains + recycled) of 170 L per capita per day for two inhabitants, of which approximately 65 L per capita per day was recycled water.

(ii) Alternative scenario – extrapolation of the baseline scenario demand to a household with four inhabitants, including the maintenance of a 65 m³ swimming pool. Pool maintenance was estimated at 11.75 m³/month (9.75 m³ for replenishing losses from use and evaporation, and 2.00 m³ for cleaning/backwashing). In months without rainfall, when recycled water production was insufficient to meet demand, supplementation with potable water from the public supply network was assumed.

2. Source of electricity for system operation:

(i) Supply from the centralized power transmission grid.

(ii) Supply from pre-installed photovoltaic panels in the residence.

2.1. Case study of an integrated rainwater and greywater recycling system

The IRGRS (Figure 1) was implemented, operated, and monitored at a single-family residence with two inhabitants located in the town of Rio Verde, Goiás, central Brazil. Rainwater is collected from the roof of the house (203.47 m²), with the first flush being redirected to the garden using a manually-operated spherical spigot to avoid introducing contaminants into the system. The rest of the water is sent to a 5-m³ underground storage tank (HDPE, Fortlev), which also receives greywater treated in a *Cyperus proliferus* Lam. wetland for 24 hours. This tank is aerated continuously with a 45 W Sarlo pump, to oxygenate the water and control odors, with its capacity being validated by the NETUNO 4.0 software.

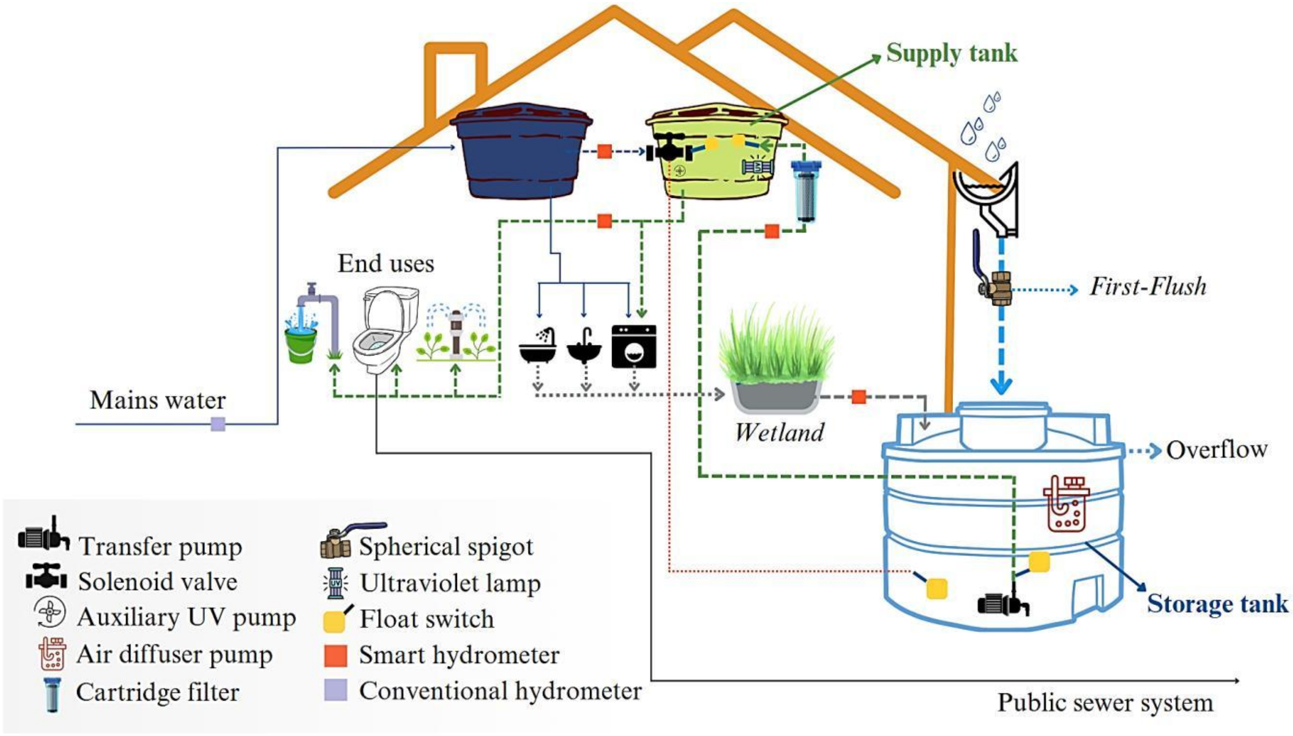

Figure 1. Diagram of the integrated rainwater/greywater recycling system (IRGRS) assessed in the present study.

The stored water is pumped (Anauger 900, 450 W) to a raised 1-m³ supply tank (HDPE, Fortlev) in the roof of the house via a cartridge filter (PP, 5 μm). This tank is disinfected continuously using an 11 W Sarlo B500 UV lamp and homogenized using a submerged 8 W Sarlo pump, both operating 24 hours a day. This recycled water is used to flush toilets, and for irrigation and washing floors, vehicles, and clothes. The system is equipped with automatic float switches (Anauger, 15 A) and a solenoid valve (generic brand), which permits the input of mains water when the water level is low. However, as the solenoid valve was not activated during the study period, it was omitted from the LCA inventory. Further information on the system is available in the Supplementary Material.

The empirical data on the amount of recycled water produced by the system were collected by hydraulic monitoring, using intelligent hydrometers, which were installed at different points within the system (see Figure 1). Four pulsed output hydrometers (UNIJATO wifi capable model SM-WA-HU, IEtecnologia) were used to measure water flow, with an ultrasonic water level sensor (wifi capable model SM-WU-HU, IEtecnologia) being used to record the level of the stored water. Each piece of apparatus has an integrated datalogger, which transmits the data to the online Monitor IE platform (IEtecnologia) for continuous storage in the cloud.

The amount of rainfall at the site, and thus, of the rainwater harvested by the system, was monitored by an autonomous rain gage (Ciclus WRF-3S, with wifi and Bluetooth connectivity) installed on the roof of the residence. This gage measures precipitation continuously (mm/min), which enables the estimation of the amount of water collected, stored, and discarded by the first-flush spigot under the roof. The data were recorded on the Weather Underground platform. The hydrometers and rain gage were not included in the assessments of the environmental and economic performance of the system, given that they were not essential operational components, but were used exclusively for monitoring.

2.2. Environmental performance

The environmental performance of the system was assessed in the construction, maintenance, and operational phases for both proposed scenarios (baseline and alternative). The Life Cycle Assessment (LCA) was conducted following the norms of ISO 14040 (2006a) and ISO 14044 (2006b), using the OpenLCA software (version 1.10.3).

2.2.1. Definition of goals

The LCA was designed to analyze and compare the environmental performance of the two study scenarios, which had distinct profiles of consumption of recycled water for non-drinking purposes. The comparative analysis focused on (i) the baseline scenario (empirical data), with the least power consumption, and (ii) the alternative scenario (simulated data), with the most power consumption. Both scenarios were implemented considering two sources of electrical power – the public grid and the solar panels installed at the residence.

In both study scenarios, mains water is provided by the public water supply, while the unusable wastewater – blackwater from the toilets and greywater from the kitchen sink – is disposed of through the public sewage system. The IRGRS operated as a complementary technology, with the principal objective of reducing mains water consumption.

2.2.2. Functional unit

The functional unit adopted here was the collection, storage, treatment, and distribution of 1 m^3 of recycled water. This definition, which is widely-used in this field of research, not only favors the interpretation of the results, but also supports direct comparisons with other systems described in previous studies (Leong et al., 2019; Zanni et al., 2019; Gómez-Monsalve et al., 2022).

2.2.3. *Operational lifespan and limitations of the system*

The operational lifespan of the IRGRS was estimated to be 50 years, which is consistent with the standard adopted in previous studies (Leong et al., 2019; Zanni et al., 2019; Gómez-Monsalve et al., 2022). This estimate is based on the fact that most of the components of the system have a projected lifespan of more than 50 years (Leong et al., 2019).

It is important to note that the centralized water supply/sewage systems were not excluded from the IRGRS in either of the study scenarios, based on a cradle-to-gate approach, without considering the environmental impacts associated with the final operational stage of the components. The assessment covers the impacts from upstream processes, including the extraction and processing of raw materials used in the manufacturing of the components, together with their respective embedded emissions, which include those related to the transportation of the components from the factory to the IRGRS. The components required for the initial implantation of the system, together with those needed for its maintenance, including planned revisions were also included in the assessment, as was any input essential for the continuous operation of the system, such as the electrical power used over the course of its lifespan.

2.2.4. *Inventory of the life cycle*

The foreground data of the IRGRS were obtained based on the consumption of the recycled water in the two study scenarios:

(i) Baseline scenario – data collected over 12 months (February 2024–January 2025) at a residence with two inhabitants, which had a mean daily consumption of 128.09 L of recycled water, with a total of 46.76 m^3 over the study period. Overall, an average of 88.07 L per day were used for flushing toilets, and 40.02 L for irrigation and washing. The extrapolation of these data indicate an accumulated total of 2,338.20 m^3 of water over the 50-year lifespan of the system.

(ii) Alternative scenario – based on the baseline data, this scenario projected the amplification of the resident family to four inhabitants with a swimming-pool of 65 m^3, which had a monthly maintenance demand of 11.75 m^3. When water was scarce, the public supply was used to complement the maintenance. In this scenario, the mean annual consumption of recycled water was 163.19 m^3, with a total of 8,159.39 m^3 over the 50 years of the system's lifespan.

The input data of the individual processes were modeled in the openLCA software, using the Ecoinvent 3.7.1 database (Ecoinvent, 2020) and the specific providers for the Brazilian context, whenever available. When Brazilian parameters were not available, data classified as RoW (Rest of World) were used.

The inventory of the IRGRS construction phase is shown in Table 1, and that of the maintenance phase, in Table 2, showing the total amounts of resources used and their values normalized in relation to the functional unit (1 m^3 of recycled water). The construction data were obtained from the project blueprint, the specifications of the system units and other information from technical catalogs, and the estimates provided by the suppliers. The operational and maintenance data were recorded during the monitoring period (baseline scenario). The foreground data were normalized by the total amount of recycled water consumed over the operational lifespan of the system, which permitted the application of standardized functional units in both scenarios.

Transportation during the construction and maintenance phases was estimated from the weight of the components and the distances between the factories and the residence. Suppliers were selected based on their geographic proximity, in order to minimize the environmental impacts associated with transportation. The principal components included: (i) PVC piping, HDPE tanks, and polypropylene (PP) filters (290 km), (ii) transfer pumps and electric floats (853 km), and (iii) submergible pumps and UV lamps (910 km), all from national suppliers. The transportation was modeled by the Ecoinvent database, using kg.km volume/distance unit.

Most of the selected suppliers (pumps, floats, UV lamps) either manufacture the best-quality products available in Brazil or are the only suppliers of this equipment. While many of these items are imported from China, Brazilian manufacturers were selected to better represent the impacts at a national level, considering the Life Cycle from the extraction of the raw material and production of the items. Despite the long distances recorded in some cases, this approach was more favorable, environmentally, in comparison with imported products.

The inventory of the operational phase (Table 3) considers the essential input for the operation of the system. Treatment processes — aeration, filtration, and UV disinfection — and pumping water require only electrical power (Jungbluth et al., 2007). The replacement of components, such as the pumps, floats, filters, and their parts, was allocated to the maintenance phase. As the cleaning of the supply tank used only stored water, with no chemical products, this process was not considered in the inventory.

Table 1. Inventory of the Life Cycle of the construction phase of the different study scenarios evaluated in the present study.

LCA Phase	Stage	Component	Ecoinvent listing	Total amount	Functional unit, scenario:		Unit
					Baseline	Alternative	
Construction	Collection / Distribution	[a]Pipes / Fittings	Polyvinyl chloride (PVC)	56.5	0.0165	0.00473	kg
	Pre-treatment (RW)	[a]Spherical spigot (First-Flush)					
	Pre-treatment (GW)	aGrease trap					
	Storage / Aeration	[a]Storage tank	High Density Polyethylene (HDPE)	114.7	0.049	0.0141	kg
	Pre-treatment (GW)	[a]Wetland tank					
	Storage / Distribution	[a]Supply tank					
	Filtration	[a]Cartridge filter with mounting bracket	Polypropylene (PP)	1	0.000428	0.0141	kg
	Storage	[b]Steel-reinforced concrete	Cement	450	0.192	0.0552	kg
			Sand	900	0.38	0.11	kg
			Water	300	0.13	0.0368	kg
			Steel	105	0.045	0.0129	kg
			#0 gravel	1500	0.64	0.184	kg
	Pre-treatment (GW)	[b]Support medium - *wetland*	#1 gravel	800	0.34	0.098	kg
	Distribution	[b]Water transfer pump1; [b]Float switches (4)[2]	Aluminum (pump body)	[1]3	0.0013	0.000368	kg
			Stainless steel	[1]1.2; [2]0.4	0.00068	0.000195	kg
			Copper	[1]0.6; [2]2.0	0.0011	0.000314	kg
			Synthetic rubber	[1] 0.2; [2]0.2	0.00016	0.0000461	kg
			Polypropylene (PP)	[1] 0.4; [2]1.2	0.00068	0.000196	kg
	Aeration / Disinfection	[c]Air diffuser[1]; [c]Auxiliary UV pump2	Stainless steel	[1]0.15; [2] 0.04	0.000081	0.0000233	kg
			Copper	[1]0.25; [2]0.05	0.00013	0.0000368	kg
			Synthetic rubber	[1]0.07; [2]0.03	0.000043	0.0000123	kg
			Polypropylene (PP)	[1]0.40; [2]0.13	0.00023	0.000065	kg
	Disinfection	[c]UV lamp	Ultraviolet lamp	1	0.00043	0.000123	item
	Shipping[a]	Plastic hydraulic components	Transport, Freight, 3.5–7.5t, EURO3	-	19.14	5.48	Kg.km
	Shipping[b]	Hydraulic motor components	Transport, Freight, 3.5–7.5t, EURO3	-	3.33	0.96	Kg.km
	Shipping[c]	Aeration/ disinfection equipment	Transport, Freight, 3.5–7.5t, EURO3	-	0.51	0.15	Kg.km

Note: [a]From manufacturer of the hydraulic components (located 290 km away); [b]From manufacturer of the motors (located 853 km away); [c]From manufacturers of the disinfection equipment (located 910 km away); [d]Local distributor.

Table 2. Inventory of the Life Cycle of the maintenance phase of the different study scenarios evaluated in the present study.

Phase LCA	System stage	Component	Replacements during lifespan	Ecoinvent listing	Total amount	Functional unit, scenario:		Unit
						Baseline	Alternative	
Maintenance	Filtration	[a]Replaceable Bracket-Mounted Filter	$^{Bs, As:}$4	PP	$^{Bs, As:}$2	0.00086	0.000245	kg
		[a]Replaceable Cartridge Filter	$^{Bs:}$99; $^{As:}$294	PP	$^{Bs:}$49.5; $^{As:}$147	0.021	0.018	kg
	Distribution	[b]Replaceable transfer pump^{1} [b]Replaceable floating switch^{2}	$^{Bs, As:}$4^{1}; 16^{2}	Aluminum (pump body)	$^{Bs, As:}$12^{1}	0.0051	0.00147	kg
				Stainless steel	$^{Bs, As:}$4.8^{1}; ^{2}1.6^{2}	0.0027	0.00078	kg
				Copper	$^{Bs, As:}$2.4^{1}; 8.0^{2}	0.0044	0.00125	kg
				Synthetic rubber	$^{Bs, As:}$0.8^{1}; 0.8^{2}	0.00064	0.000184	kg
				PP	$^{Bs, As:}$1.6^{1}; 4.8^{2}	0.0027	0.000782	kg
	Aeration and Disinfection	[c]Replaceable air diffuser pump^{1} [c]Replaceable auxiliary UV pump^{2}	$^{Bs, As:}$4	Stainless steel	$^{Bs, As:}$0.6^{1}; 0.16^{2}	0.00033	0.0000931	kg
				Copper	$^{Bs, As:}$1.0^{1}; 0.05^{2}	0.00051	0.000147	kg
				Synthetic rubber	$^{Bs, As:}$0.28^{1}; 0.12^{2}	0.00017	0.000049	kg
				PP	$^{Bs, As:}$1.6^{1}; 0.52^{2}	0.00091	0.00026	kg
	Disinfection	[c]Replaceable UV lamp	$^{Bs, As:}$49	Ultraviolet lamp	$^{Bs, As:}$49	0.021	0.00601	item
	Shipping[a]	All plastic hydraulic components[a]	-	Freight, commercial vehicle	$^{Bs:}$14,935; $^{As:}$43,210	6.38	5.31	Kg.km
	Shipping[b]	All motor components[b]	-	Freight, commercial vehicle	$^{Bs, As:}$31,390	13.31	3.81	Kg.km
	Shipping[c]	All desinfection equioments[c]	-	Freight, commercial vehicle	$^{Bs, As:}$13,013	5.56	1.59	Kg.km

Note: [a]From manufacturer of the hydraulic components (located 290 km away); bFrom manufacturer of the motors (located 853 km away); cFrom manufacturers of the disinfection equipments (located 910 km away); Bs = Baseline scenario; As = Alternative scenario.

Table 3. Inventory of the Life Cycle of the operational phase of the different study scenarios evaluated in the present study.

Phase LCA	System stage	Component	Energy Use (kWh) per Functional unit		Observations
			Baseline	Alternative	
Operation	Treatment/ Aeration	Air diffuser pump (45W)	6.73	2.19	$^{Bs, As:}$ Operating 24 hours a day
	Distribution	Water transfer pump (450W)	0.4	1.37	$^{Bs:}$ Operating for 0.5 hours twice a week $^{As:}$ Operating for 1.5 hours seven times a week
	Treatment/ Desinfection	UV lamp (11W)	1.64	0.53	$^{Bs, As:}$ Operating 24 hours a day
		Auxiliary UV pump (8W)	1.2	0.39	$^{Bs, As:}$ Operating 24 hours a day

Note: Bs = Baseline scenario; As = Alternative scenario; *Ecoinvent process* → 1) On-site, low voltage solar power production; 2) High voltage electricity, Brazilian production mix (values include 13.5% transmission grid losses).

The Brazilian power grid was modeled from the Ecoinvent database as a high voltage production mix, with transmission line losses of 13.5% (ANEEL, 2021), which were included in the values inventoried. The National Energy Database (BEN, 2024) shows that the sources of the Brazilian grid include hydropower (58.9%), wind (13.2%), nuclear (2.~~0~~%), and solar power (7.0%), natural gas (5.3%), sugarcane bagasse (5.1%), black liquor (2.1%), coal (1.2%), diesel (0.6%), other renewable (0.8%) and non-renewable (1.6%) sources, and imports (2.1%). The presence of solar panels (Ecoinvent: on-site, low voltage photovoltaic production) at the study residence contributed to the variability in the environmental impacts associated with the consumption of power, by reducing the dependence of the system on the national grid.

2.2.5. *Evaluation of the impact of the Life Cycle*

In both scenarios, the potential environmental impacts of the system were assessed based on the ReCiPe 2008 method, with the Hierarchist (H) perspective, which is considered to be an intermediate approach, and is widely used in LCA studies (Boldrin et al., 2022; Huijbregts et al., 2017). Indices of the midpoint impact and final damage (endpoint) were employed here to provide a comprehensive analysis that was comparable with the potential environmental effects. This approach has been applied in previous studies of integrated rainwater/greywater recycling systems (Marinoski et al., 2019; Zanni et al., 2019; Gómez-Monsalve et al., 2022).

The following impact categories were considered at the midpoint in the LCA: climate change (kg CO_2-eq), fossil fuels depletion (kg oil-eq), freshwater ecotoxicity (kg 1.4-DCB-eq), freshwater eutrophication (kg P-eq), human toxicity (kg 1.4-DCB-eq), ionising radiation (kg U235-eq), marine ecotoxicity (kg 1.4-DCB-eq), marine eutrophication (kg N-eq), metal depletion (kg Fe-eq), ozone depletion (kg CFC-11-eq), terrestrial acidification (kg SO_2-eq), and water depletion (m^3). Particulate matter formation, photochemical oxidant formation, the occupation of agricultural and urban land, and terrestrial ecotoxicity were excluded from the analysis given that their impacts were negligible overall, in addition to being absent from the studies used for comparison (Rodrigues et al., 2023). At an endpoint level, the potential impacts were assessed in terms of the three damage categories established by the ReCiPe 2008 method: human health, ecosystem quality, and resource scarcity.

2.3. Economic analysis

The economic analysis of both scenarios was based on the projection of the cashflow over the operational lifespan of the IRGRS. This analysis considered the initial investment for the implantation of the system (materials and labor), operational costs, and the savings made on mains water and sewage bills, according to the data obtained for each scenario. Details of the parameters, including the calculations and estimated values, are available in the Supplementary Material.

The costs of the implantation of the IRGRS were estimated based on the prices of the individual components (excluding the hydrometers and rain gage). The cost of the solar power system were also excluded from the economic analysis, given that it was installed prior to the beginning of the study.

The operational costs include the consumption of electricity by the pumps and the UV lamp, in addition to the expenses of the periodical maintenance, such as the cleaning of the supply tank, and the replacement of the filter cartridges. The cartridge was replaced once every six months in the baseline scenario, and every two months in the alternative scenario, due to the increase in the demand for recycled water.

The economic viability of the proposed system was analyzed based on three standard financial indices that are widely used in the assessment of investments – Simple Payback, the Net Present Value (NPV), and the Internal Rate of Return (IRR). While the payback estimates the time necessary for the return on an investment, the NPV is the aggregated value accumulated over time, and the IRR provides a measure of the relative profitability of the project. The equations and calculation methods follow Zavala et al. (2016) and Domínguez et al. (2017).

A Minimum Activity Rate (MAR) of 3% per year was adopted here. This value is typically used in environmental, social or residential projects with a focus on sustainability and the economy of resources, rather than financial returns. As the investment analyzed here was personal, and had no external financing or expectation of profits, the MAR reflects a low-risk conservative alternative, which is compatible with applications that have a real rate of nearly zero. Zavala et al. (2016) adopted a similar approach, fixing MAR at 3%, based on the contemporary inflation rate.

2.3.1. Capital Costs

The estimates of the capital costs for the installation of the system were based on data obtained from local and regional suppliers, using 2022 as a reference (which is when the system was constructed). This approach consists of an analysis of the mean local prices of materials, equipment, and specialized services, to establish the real economic conditions of the locality, and a robust baseline for the assessment of viability. A detailed description is available in the Supplementary Material (Tables S1 and S2).

The values of the materials and equipment were obtained from billing lists of local suppliers for similar projects, based on the predicted consumption of material, including the tanks, pipes and fittings, pumps, filters, valves, other construction materials, treatment equipment, and reinforced concrete for structures. The labor costs were calculated based on the mean regional pay rates for bricklayers (hourly rate for residential services), electricians (daily rate for the installation of electrical equipment), and backhoe operators (hourly rate for the excavation of the underground installations).

2.3.2. Maintenance and Operational Costs

The operational costs include the consumption of electricity, based on the tariffs adopted for each scenario (see below). The costs of maintenance services, including the replacement of the filter cartridge, were also considered. The supply tank was cleaned without using detergents, which reduced costs in comparison with conventional procedures.

The consumption of electricity by the principal devices used by the IRGRS system was considered in the analysis of operational costs. The aeration pump, UV pump, and auxiliary pump were working 24 hours a day. The transfer pump, which pumped the recycled water to the supply tank, was turned on twice a week for 0.5 hour in the baseline scenario and daily for 1.5 hours in the alternative scenario, due to the increase in demand for recycled water. The costs of electricity were excluded from the analyses of the solar-powered scenarios, given that the available system covered the full demand of the IRGRS equipment.

2.3.3. Electricity Tariffs

A working solar power system had already been installed on the property prior to the present study period and was registered prior to January 6th, 2023. This exempts the system from tariffs, in accordance with current Brazilian energy distribution regulations under Federal Law No. 14,300/2022 (Brazil, 2022). In fact, the excess power generated by the system is fed into the national grid to offset any additional charges associated with the use of power from the grid. In the scenarios powered by the public grid, the calculations were based on the tariff for unsubsidized residential consumers established for the state of Goiás by National Electrical Energy Agency (ANEEL) resolution 3,407/2024, which is R$0.74593 per kWh.

The annual adjustment of the tariff applied in the simulations was fixed at 3.5% per annum, which is consistent with the historical mean of the adjustments practised by ANEEL for class B1 residential consumers over the past decade (3–6% per annum). This estimate is based on official data and the value of 3.5% established by ANEEL in their InfoTarifa bulletin, published in April 2025, which is below the predicted inflation rate of the respective year. This estimate is compatible with the parameters used in previous studies (Rosa & Ghisi, 2021;

Zhang et al., 2021), which have adopted a conservative approach to the operational costs associated with the consumption of electricity in re-use systems. The value is also consistent with the recent technical reports of the national electrical sector.

2.3.4. Water and Sewage Tariffs

The water and sewage tariffs used in the present study were based on the rates practised by the local sanitation department, SANEAGO, as of February 28th, 2024. The tariffs vary progressively according to the volume of water consumed. The basic water tariff is R$5.28 per m^3 for the first 10 cubic meters consumed in a month. Above this threshold, a progressive tariff structure is applied, according to the volume of water consumed. The sewage tariff has two components: (i) collection and removal, R$ 4.22 per m^3, and (ii) treatment, R$1.06 per m^3.

The total cost of water and sewage was thus R$10.56 per cubic meter for water consumed up to 10 m^3 per month. This value was used to calculate the costs/savings of the water (mains/recycled) consumed in both scenarios.

The variation in costs over the study period was taken into account using an annual adjustment of 5.52%, which is the median of the historical adjustments practised by the Goiás sanitation department between 2006 and 2025 (SANEAGO, 2025). This value was used as a parameter of the adjustment of the tariff in the predictions of cash flow and the analysis of the economic viability of the proposed system, given that the tariffs are practised throughout the state of Goiás.

3. RESULTS AND DISCUSSION

3.1. Life cycle impact assessment

The Life Cycle Assessment (LCA) presented here compared two scenarios of use of the same integrated rainwater and greywater recycling system (IRGRS). This assessment employed an innovative approach based on internal comparison between baseline and alternative scenarios, considering actual differences in the use of the system, such as the number of residents and the use of recycled water for a swimming pool. This approach contrasts fundamentally with the comparison between centralized and decentralized systems, which has been the focus of previous studies (Gómez-Monsalve et al., 2022; Marinoski & Ghisi, 2019; Leong et al., 2019; Zanni et al., 2019).

The environmental impacts of the construction, maintenance, and operational phases were compared using the midpoint categories of the ReCiPe method, with the public grid as the source of power (Figure 2).

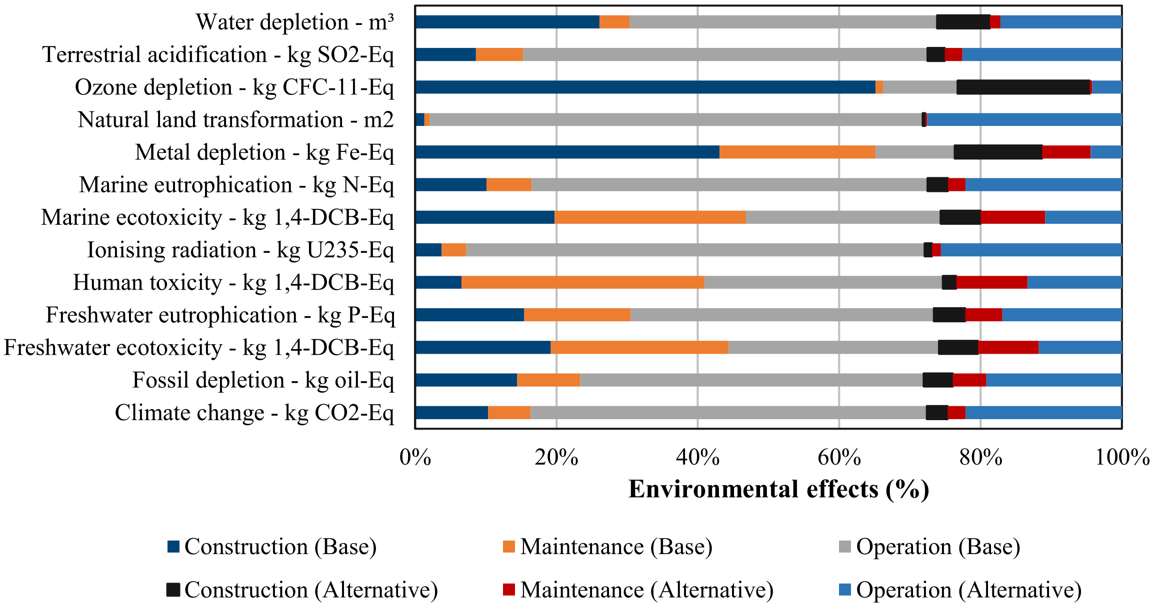

Figure 2. Normalized environmental effects observed in the life cycle phases of each IRGR system using the ReCiPe midpoint method.

The indicators for the midpoint impact categories per functional unit are detailed in the supplementary material (Table S3) for all phases and scenarios. The results indicate that, in the baseline scenario, the operational phase accumulates the largest portion of the environmental impacts, due primarily to the continuous consumption of electricity, followed by the maintenance and construction phases, with smaller, but still sizeable contributions. These findings are consistent with those of previous studies, which have also shown that the operational phase produces the most impact (Gómez-Monsalve et al., 2022; Marinoski & Ghisi, 2019; Leong et al., 2019; Zanni et al., 2019; Wang, Ni, et al., 2024; Allami, Sorour, et al., 2023; Skultetyova, Dubcova, et al., 2016).

In both scenarios, the operational phase represents the principal contribution to the impacts, due primarily to the consumption of electricity by the machinery. The alternative scenario nevertheless presents a reduction of more than 50% in comparison with the baseline scenario, a pattern repeated in the maintenance and construction phases. This reduction is derived from the increase in the use of recycled water from the IRGR system. In the alternative scenario, the system not only supplies twice as many residents, but is also used for the maintenance of a swimming pool, resulting in the dilution of the impacts per cubic meter.

Given this, the alternative scenario had a better environmental performance, not because it demanded less resources, in absolute terms, but because it supported the more intensive and efficient use of the water produced by the system. This re-emphasizes the importance of considering not only the inputs and technology involved in the process, but also the use of and demands on the system, which determine the sustainability of water re-use systems. A similar dilution of impacts per functional unit was observed by Zanni et al. (2019), with a reduction of up to 70% through the use of a greywater reuse system for 30 inhabitants, as well as by Leong et al. (2019), when a hybrid rainwater-greywater system was adapted to commercial buildings, and by Marinoski & Ghisi (2019), with clear gains in low-income housing projects.

Climate change, ecotoxicity, and human toxicity are the most relevant impact categories in the two study scenarios, with the operational phase being the principal period responsible for these effects, especially in the baseline scenario. In the alternative scenario, while the operation of the system continued to have a significant contribution, the redistribution of the impacts reflects greater environmental efficiency and the better use of the recycled water.

Despite the increase in the consumption of water in the alternative scenario, the system did not have a direct impact on water resources, given that the extra water was recycled. The fact that this water did not enter the public sewage or drainage systems also represents a reduction in the pressure on public infrastructure and may have contributed to the mitigation of flooding. However, this benefit is not picked up by the water depletion category, which does not reflect adequately the positive effects of local water re-use. Zanni et al. (2019) and Leong et al. (2019) also highlighted this methodological limitation, that is, the inability of traditional LCA methods to incorporate the external environmental benefits associated with decentralized systems.

The impacts recorded in the endpoint impact categories (ecosystem quality, human health, and resource use) in the operational phase of the baseline and alternative scenarios were compared between the use of electricity from the public grid (grid mix) and solar power (Figure 3). In both scenarios, the impacts on human health were most prominent, principally when using power from the grid.

The substitution of the public grid with solar energy represents a potential solution for the reduction of the impacts of the operational phase, especially considering the viability of the installation of the solar panels on the roof of the residence. Zanni et al. (2019) concluded that the substitution of conventional sources of electricity by solar power reduced the impacts of the climate change category by up to 99% in the scenarios with larger number of users, together with significant reductions in Human Toxicity (HT) and Ecotoxicity, due primarily to the elimination of the emissions associated with the generation of electricity for the grid. The use of solar panels also mitigated the impacts of the resource depletion category, and overall, it is clearly a more sustainable solution, even when the lifespan of the panels and their components are taken into account.

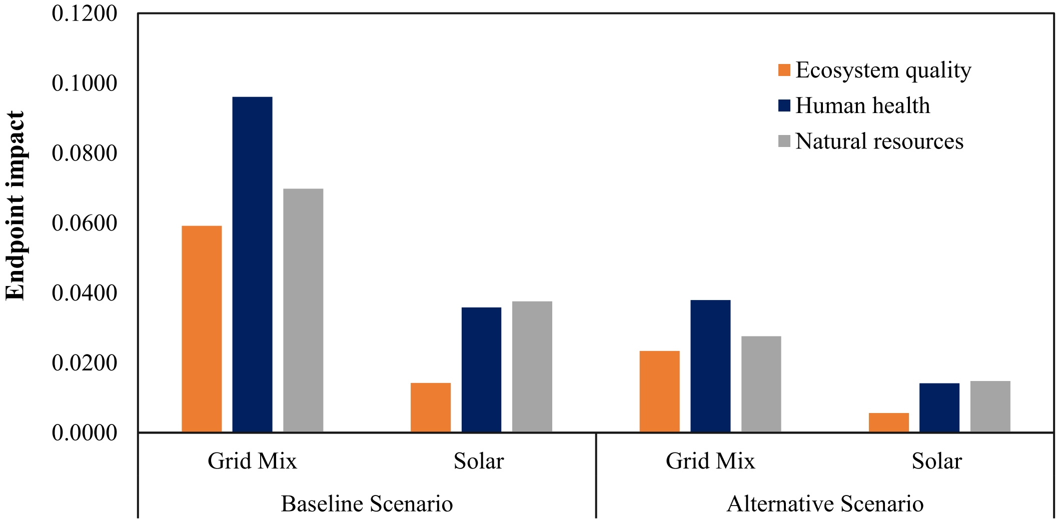

Figure 3. Comparison of the endpoint impacts of the operational phase in the two scenarios assessed here, considering the two different sources of electricity.

However, solar power also has limitations. The most widely-used systems require the use of inverters, which consume electricity, and the composition of their electronic components is also problematic. The operational lifespan of solar panels is also limited, typically to 20–30 years, after which, they require adequate disposal or recycling, which represent a major environmental challenge.

Gómez-Monsalve et al. (2022) also obtained similar results when comparing different sources of electricity in Colombia, where the use of solar power reduced consistently the total impact on the endpoint categories by more than 40%, in comparison with the grid mix. Even taking the production and lifespan of the solar panels into account, then, the system with solar power will have the smallest impact, accumulated over time, with a perceptible improvement in the operational phase, which had the most impact due to the consumption of energy, as observed here.

While the Brazilian electrical matrix is predominantly renewable, especially in comparison with the global scenario, due to the participation of hydropower, wind power, and biomass, around 13.9% of its energy is still supplied by non-renewable sources, including coal, oil, and natural gas (EPE, 2024). It is important to note here that the modeling, which was based on the Ecoinvent data on the Brazilian grid, did not contemplate the the impacts associated with the implantation of the transmission and distribution infrastructure, nor the losses incurred across the supply chain. By contrast, the process used for the solar power included the complete life cycle of the system, including the inverter, the operational lifespan of the solar panels (mean performance), and the upstream activities (extraction of raw materials and manufacturing), as well as the treatment and consumption of the water used to clean the modules.

Given this, the impacts attributed to the electricity from the public grid tend to be underestimated, in particular in the case of the categories related to human health and ecosystem quality, which compromises the comparison between the sources. Zanni et al. (2019) also identified this methodological limitation, i.e., that conventional LCA methods tend to underestimate the actual impacts of grid power by not considering the effects of transmission and distribution adequately. In the present study, this distortion was corrected by adding 13.5% to the values of the grid (ANEEL, 2021). Zanni et al. (2019) and Gómez-Monsalve et al. (2022) observed that solar power obtained a better environmental performance, even when the impacts associated with manufacturing and disposal are taken into account, which reinforces its sustainability for the operation of decentralized systems.

3.1.1. Relative contribution of the materials and components

The relative contributions of the materials and components used in the construction phase to the midpoint impact (Figure 4) indicated that the principal components responsible for the environmental impacts in both scenarios were HDPE (used to make the tanks and line the wetland environment), cement and steel (used in the reinforced concrete of the underground storage tank), and the transportation of materials, in particular those not available from local suppliers. These items dominate the impacts of many categories, reinforcing the findings of Zanni et al. (2019), who identified these same materials as the most critical in the construction phase of decentralized systems.

In the HT category, the predominance of the steel and cement of the reinforced concrete, the PVC and HDPE, and the copper, aluminum, and steel components of the pumps indicates that the metallic components and plastic materials play an important role in this impact. This reflects their production processes, which involve the emission of toxic substances, such as sulphur dioxide, heavy metals, volatile organic compounds, and other pollutants, which are all associated with risks to human health, in particular in communities adjacent to industrial zones.

Components such as steel (reinforced concrete), aluminum, and copper dominate Metal Depletion (MD), especially in the baseline scenario. In turn, the Transformation of Natural Land (TNL) is impacted strongly by the use of sand and gravel (concrete and wetland), in particular in the baseline scenario. The contributions of the OD, TA, and WD categories were concentrated primarily in PVC, cement, mains water, and transportation, with the alternative scenario presenting a degree of redistribution, which indicates a shift in the profile of impact.

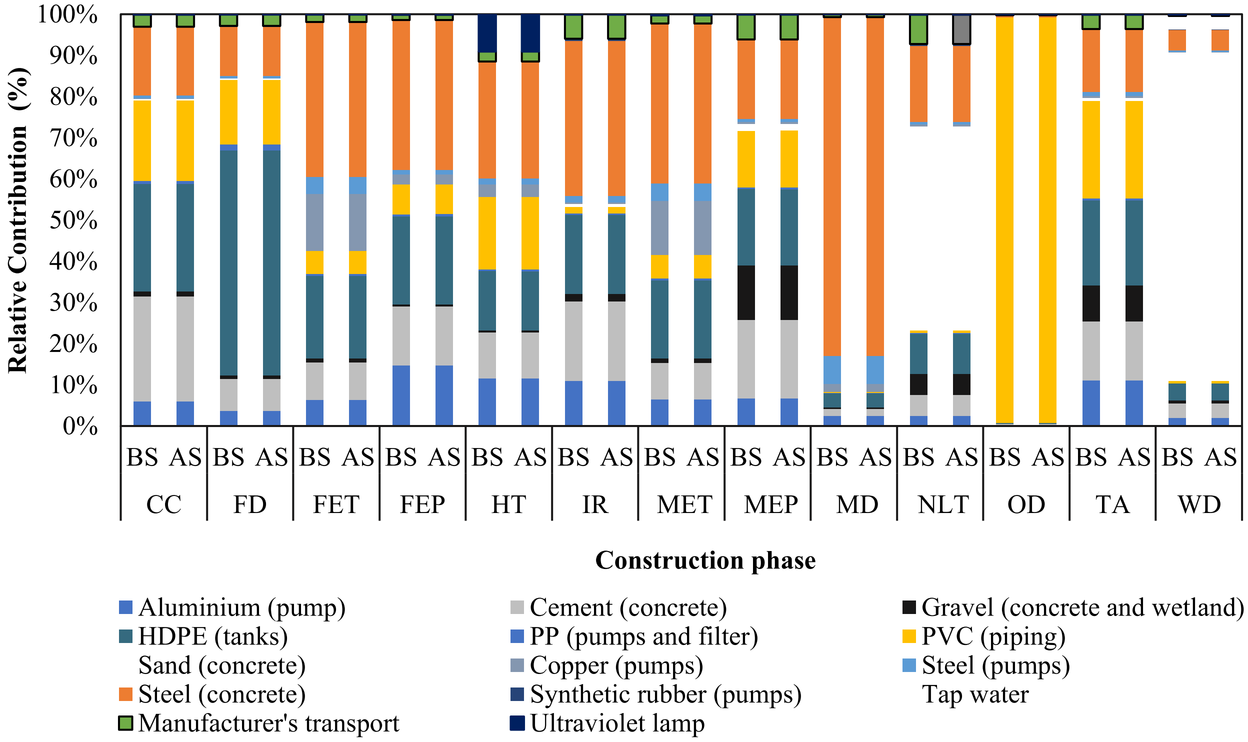

Figure 4. The relative contribution of the components and inputs of the Baseline (BS) and Alternative Scenarios (AS) in the Construction phase. Note: CC = Climate Change; FD = Depletion of Fossil Fuels; FEC = Freshwater Ecotoxicity; FEU = Freshwater Eutrophication; HT = Human Toxicity; IR = Ionising Radiation; MEC = Marine Ecotoxicity; MEU = Marine Eutrophication; MD = Metal Depletion (MD); TNL = Transformation of Natural Land; OD = Ozone Depletion; TA = Terrestrial Acidification; WD = Water Depletion).

However, it is important to note that the materials used to make the pipes and the tanks, including HDPE, PVC, cement, steel, sand, and gravel, are the principal components responsible for the structural longevity of the system, which has a predicted lifespan of approximately 50 years. As these components do not require frequent replacement, the impacts associated with their production, transportation, and installation tend to be diluted over their long operational lifespan, contributing to a more balanced environmental performance over the long term.

This is consistent with the findings of Leong et al. (2019), Zanni et al. (2019), Marinoski & Ghisi (2019), Kobayashi et al.(2020), Gómez-Monsalve et al. (2022), Gallagher and Gill (2022), Rodríguez et al. (2021), who all adopted similar timelines (20–50 years) and concluded that the durability of the materials is a key factor for the reduction of environmental pressure in the initial phase of the Life Cycle. Zanni et al. (2019) and Gallagher and Gill (2021) emphasize that the impacts of the construction phase tend to be compensated for when the materials have a long lifespan and low frequency of replacement, which improves the environmental performance per cubic meter of recycled water. Leong et al. (2019) also observed that, in well-designed hybrid systems, the impacts of the construction tend to become secondary in comparison with the operational phase, especially when the structural components do not require replacement over time.

The reduced impacts observed in the alternative scenario resulted primarily from the more intensive use of the system, that is, the consumption of a much larger volume of recycled water over the course of its operational lifespan. This increase in the consumption of recycled water contributed to a proportional reduction in the environmental impacts per functional unit. In general, these findings demonstrate the decisive role of recycled water in the mitigation of the impacts of the life cycle. The alternative scenario also resulted in the redistribution of the environmental burden between the materials and components employed in the system, by reducing the dependence on the inputs with a more intense impact, especially those of fossil or metallic origin. This resulted in a more efficient environmental performance in terms of the relative contribution of the different materials.

In the maintenance phase (Figure 5), the relative contribution of the materials to the different categories of environmental impact also shifted between scenarios, with emphasis on the replacement of components such as pumps and UV lamps, the transportation of materials, and the plastic in the filter cartridges. Here, the environmental impacts are concentrated in the HT, CC, and FD categories, with HT being the most prominent, in particular in the baseline scenario, reflecting the contribution of the UV lamp, which has a short lifespan and complex composition, requiring frequent replacement, involving potentially toxic industrial processes. This pattern is consistent with the findings of Marinoski & Ghisi (2019), who identified significant impacts from disinfection using sodium hypochlorite, primarily in categories such as aquatic ecotoxicity, photochemical oxidant formation, ozone depletion and eutrophication, due to the generation of halogenated subproducts. Leong et al. (2019) also observed that the combined use of ozone and chloride aggravates impacts related to acidification, toxicity, and power usage, in particular in systems with inefficient use of the treated water.

While disinfection by UV minimizes the formation of dangerous chemical subproducts, its environmental performance depends on the durability of its components, the energy source used, and the life cycle of the equipment. The substitution of the grid mix by solar power, as in the present study, is known to be effective for the reduction of the impacts associated with the use of UV lamps, thus contributing to the environmental viability of this technology in a residential context.

The polypropylene (PP) present in the pumps and the filter cartridges was also important in the CC and FD categories. In the alternative scenario, the increase in the pumping of recycled water reduced the operational lifespan of the filters, with the frequency of replacement of the refills being increased from every six months to every two months, which intensified the environmental burden associated with PP, a material of fossil origin whose production is energy-intense.

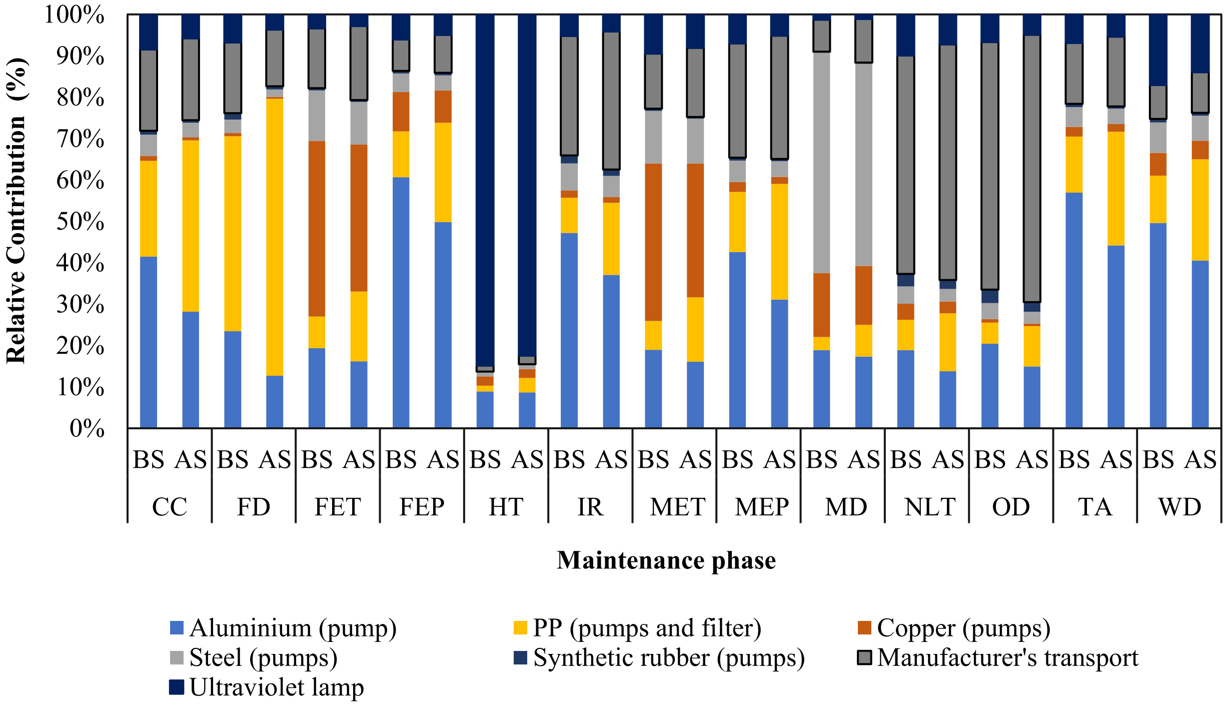

Figure 5. The relative contribution of the components and inputs of the Baseline (BS) and Alternative Scenarios (AS) in the maintenance phase. Note: CC = Climate Change; FD = Depletion of Fossil Fuels; FEC = Freshwater Ecotoxicity; FEU = Freshwater Eutrophication; HT = Human Toxicity; IR = Ionising Radiation; MEC = Marine Ecotoxicity; MEU = Marine Eutrophication; MD = Metal Depletion (MD); TNL = Transformation of Natural Land; OD = Ozone Depletion; TA = Terrestrial Acidification; WD = Water Depletion).

The transportation of the components was also relevant to a number of different categories, such as FEP, IR, TA, and WD. These impacts were derived principally from the consumption of fuels and their emissions, for the distribution of the material. In turn, the copper used in the pumps contributed significantly to ecotoxicity in aquatic environments, given its toxic potential and the environmental damage caused by its mining and smelting.

In both scenarios, the maintenance impacts were concentrated in the substitution of pumps, UV lamps, PP filter cartridges, and the transportation of these components. Even so, the alternative scenario still had the better environmental performance, due primarily to the dilution of impacts over time, by the much larger amounts of recycled water consumed, which favored a more efficient and environmentally balanced operation.

Given the overall contribution of the maintenance phase to the environmental impacts of the study system, an important recommendation that can be derived from these findings would be to substitute the traditional model of the replacement of electromechanical components with more sustainable strategies of corrective maintenance and reconditioning, as mandated by the principles of the circular economy. These practices are intended to prolong the operational lifespan of the machinery, reduce the demand for raw materials — in particular, metals and polymers — and mitigate the environmental impacts associated with the production, transportation, and disposal of the used components.

In addition to their environmental benefits, these strategies are especially relevant to localities that are geographically distant from industrial centers. The consolidation of a local network of technical services for the maintenance of IRGR systems would not only contribute to the reduction of costs, but also the generation of income and employment, as well as new business opportunities. All these factors would also favor the autonomy of the system, while also reducing its environmental footprint and encouraging integrated regional development.

3.1.2. Endpoints in the internal comparison between the scenarios of the proposed system

By comparing two operational scenarios for the same IRGRS, the present study adopted a novel approach, which contrasted with the traditional comparisons with centralized models, which have often been based on non-equivalent parameters, such as water and sewage stations located in other regions or even countries. The analysis of the scenarios proposed here considered distinct levels of consumption of the recycled water, which permitted simulations found on local data, consistent with the urban, climatic, and technological reality of the system.

In particular, (Figure 6), the alternative scenario resulted in a reduction of over 50% in the endpoint impacts on the three categories assessed. This was the direct result of the much greater volume of recycled water consumed, which diluted the impacts per functional unit and improved the environmental efficiency of the system as a whole.

These findings are consistent with those of Zanni et al. (2019), who concluded that subutilized systems – such as low-demand rainwater capture systems – may generate greater environmental impacts than conventional systems. On the other hand, more intensive-use systems, with recycled water being applied to multiple activities, achieved a better performance over the course of the life cycle. Marinoski & Ghisi (2019) also demonstrated that the scale of use and the local socioeconomic context had a direct influence on the environmental results of hybrid re-use systems. Gómez-Monsalve et al. (2022) emphasized the importance of the continuous use of recycled water and the adequate sizing of the systems in tropical regions. Likewise, Leong et al. (2019) emphasized the need to adapt the system to the occupation density and seasonal variability, which would help to improve the environmental performance, principally in the categories of toxicity and consumption of resources.

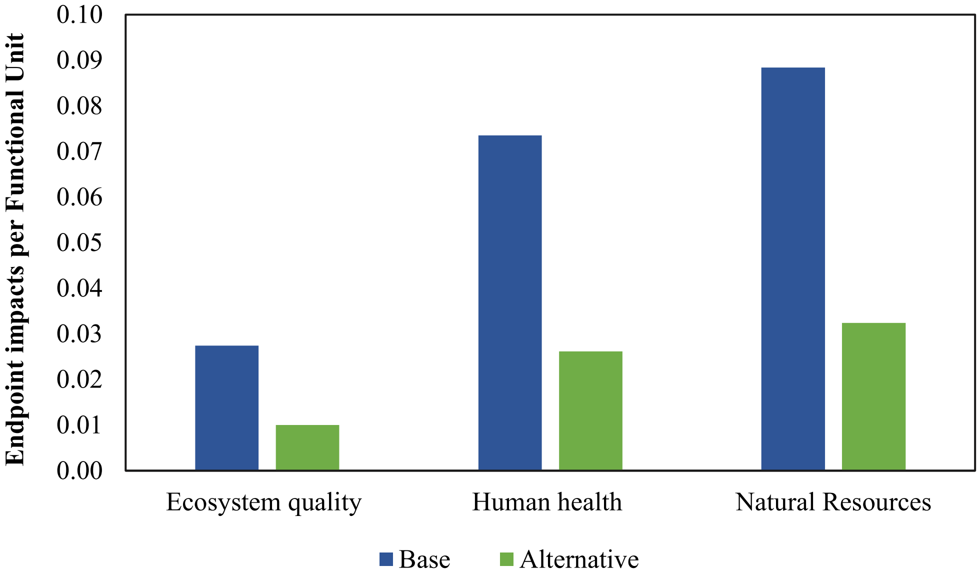

Figure 6. Comparison of the ReCiPe endpoint impacts for the Baseline and Alternative scenarios.

Despite the good results obtained in the alternative scenario, it is important to note that the system was still operating below capacity. The simulation of the alternative scenario considered a consumption of 8,159.39 m³ of recycled water over 50 years. However, the actual data obtained from the monitoring of the system in 2024 indicate that 284.63 m³ of rainwater and greywater were collected in this year alone, in spite of the occurrence of a prolonged drought between May and September, and the fact that the greywater was produced by only two residents. These data indicate a potential minimum production of 14,231.68 m³ of recycled water over 50 years. This divergence between the installed capacity and the volume of water effectively consumed reflects the sub-use of the infrastructure, even in an optimized scenario, which reinforces the need for strategies that amplify the use of recycled water and improve the efficiency of the system.

The analysis of the different scenarios of the consumption of the recycled water revealed concrete opportunities for the improvement of IRGR systems. Strategies such as the more efficient exploitation of seasonal surpluses and the diversification of non-potable consumption, including indirect re-use through soil infiltration and irrigation for food production, are clearly viable alternatives, which are aligned with Sustainable Development Objectives, especially those related to food and water security. In specific contexts, it would also be possible to evaluate the technical potential of the use of recycled water for human consumption, as long as energy efficiency and the economic and operational viability of the system can be guaranteed, as well as the quality of the water.

3.2. Economic assessment

3.2.1. Capital, operational, and maintenance costs, and water savings

The total initial investment for the implementation of the IRGRS was R$9,570.63, including R$8,295.63 in components and R$1,275.00 in labor. The most expensive individual item was the 5 m³ storage tank, which cost R$2,636.90, approximately a third of the total cost of materials. This is consistent with the study of Rosa & Ghisi (2020), who emphasized that the storage infrastructure is the critical component, not only for the functionality of the system, but also of the overall costs of the integrated recycling systems.

The operational costs varied between the scenarios due principally to the use of the transfer pump (450 W), which consumed 0.36 kWh per week in the baseline scenario and 3.78 kWh per week in the alternative scenario. The consumption of the machinery that was in constant use, such as the aeration pump (45 W), UV lamp (11 W), and auxiliary pump (8 W), was constant in the two scenarios. Given these parameters, the annual costs of the operational and maintenance phases reached a total of R$707.17 in the baseline scenario and R$1,079.63 in the alternative scenario, reflecting the increase in the consumption of electrical energy (from 466.0 kWh to 643.8 kWh) and the more frequent replacement of the filter cartridges (from twice to six times a year).

In the baseline scenario, savings of mains water were between 26.01% and 48.98%. This variation reflects the influence of seasonal fluctuations in rainfall, given that, during the dry season, which lasted six months, the system was supplied only by greywater. In the alternative scenario, which involved a larger area of capture and a larger number of consumers, water savings exceeded 70% in December and January. The mean annual saving was approximately 40% for both scenarios. These results are consistent with those of previous studies, such as those of Ghisi and Ferreira (2007), who reported savings of 36.7–42.0%, Rosa & Ghisi (2020), who recorded savings of 51.6%, Marinoski & Ghisi (2019), savings of 41.9%, and Gómez-Monsalve et al. (2022), with 42.5%. Negative performances, such as those reported by Castleton et al. (2014), that is, -8.5% to -10%, reinforce the importance of the adequate adjustment of the dimensions of the system in relation to the demand for water and its local availability. The monthly savings of mains water and the volume of recycled water consumed by the study household are shown in the Supplementary Material (Table S5).

3.2.2. Economic performance of the scenarios

The principal economic indices of the four scenarios simulated for the IRGR system, considering a lifespan of 50 years and a MAR of 3% per year, are shown in Table 4. These data encompass the consumption of water prior to the implementation of the system, estimated savings, the annual operating costs, and the predicted adjustments in the tariffs.

The financial analysis, with a MAR of 3%, indicated that the alternative scenarios were more economically viable than the baseline scenarios. The results demonstrated that the use of the solar power potentializes this viability even further, with better returns on investment and shorter payback time. The baseline scenarios were less attractive, especially when dependent on power from the grid, which reflects their greater sensitivity to the variation in operational costs. These findings are consistent with those of Domínguez et al. (2017), who related the reduced financial performance of re-use systems to the impact of the consumption of conventional electricity.

Table 4. Cost indices for the scenarios modeled here, considering an exchange rate of R$1 = US$0.1769.

Scenario	**Net Present Value (USD)**	**Internal Rate of Return (% per annum)**	**Discounted payback (years)**
Baseline (solar power)	$4,937.30	0.0796	24
Baseline (grid mix)	$1,570.00	0.0471	40
Alternative (solar power)	$21,759.60	0.1772	8
Alternative (grid mix)	$17,096.00	0.1396	12

Ghisi and Oliveira (2007) reported a mean payback of 60 years, reflecting reduced economic incentives for systems installed in single-family residences, while Ghisi and Ferreira (2007) recorded a payback of 5.7 years for large-scale multi-family systems, which is more favorable than the alternative scenarios tested here. Ghisi et al. (2014) obtained even better economic results (NPV = US$34,724.02, discounted payback = 1.8 years), albeit with a low MAR (0.68% per month), which favors the economic indices. Despite these findings, the IRR reported in this study (5.37% per month) is comparable to the values obtained here in the baseline scenarios.

Zavala et al. (2016) obtained the highest NPV (US$50,483.20) found in the references compiled here, albeit with a moderate IRR (4.6%), similar to the baseline scenario with grid power recorded here, indicating that high accumulated returns are not always an indication of attractive percentage gains. By contrast, Domínguez et al. (2017) recorded a much less favorable economic performance (NPV = US$337, payback = 30 years, IRR = 4.69%), while Oviedo-Ocaña et al. (2018) reported an intermediate performance (NPV = US$4,053, payback = 23 years, IRR = 6.5%), close to that of the baseline scenarios analyzed here. Rosa & Ghisi (2020) found a much more favorable payback (5.3 years) despite the modest NPV (US$1,958.67). This was among the best alternative scenarios analyzed.

With a very low payback (4.4 years), Zhang et al. (2021) recorded a high level of economic viability, even without reporting the NPV or IRR. Rosa & Ghisi (2021) recorded a more modest economic performance (payback = 9.5 years), which is similar to the baseline scenario with solar power analyzed here, while Alarcón et al. (2021) obtained an intermediate payback, of 11 years, for a multi-family system, which is comparable with the alternative scenario with grid power assessed here.

The alternative scenarios assessed here had a robust economic performance, which was among the best recorded to date, in terms of the IRR and NPV values, a scenario favored by the 50-year lifespan considered in the financial calculations. While not reaching the level of some previous studies with highly favorable conditions (e.g., Ghisi et al., 2014; Zhang et al., 2021), these findings did confirm the economic viability of the integrated systems for the re-use of rainwater and greywater, especially when combined with solar power, which contributed to urban sustainability and water security. Further details on the cost indicator comparisons available in the literature, as well as their relation to previously reported studies, are provided in the supplementary material (Table S4).

3.2.3. Sociocultural considerations and the role of non-financial sustainability

While the analysis of economic viability is a fundamental consideration in the assessment of projects of sustainable development, limiting the adoption of innovations such as the IRGRS exclusively to financial indices may lead to decisions that are out of step with current environmental challenges. Here, in fact, the total cost of the system corresponded to only 1.6% of the capital invested in the construction of the residence. This percentage is equivalent to or much lower than the cost of many items that have only esthetic value, such as doors, paneling, and luxury fittings, that do not have any environmental or social function.

Architectural projects may exclude an IRGRS due to its perceived interference with the visual harmony of the design, although these questions can be resolved with adequate planning. For example, the storage tank can be installed underground, where it is completely invisible, while the artificial wetland can be integrated into the design of the garden, adding both ecological and ornamental value. When an IRGRS is included in the project from the start, it can be visually discreet, and not affect either the esthetics or the functionality of the building in any way.

Decentralized systems, such the IRGRS, play a fundamental role in the mitigation of water scarcity, the reduction of the pressure on public infrastructure and the prevention of urban flooding, benefits that are rarely contemplated by traditional financial indices. As proposed by

Rosa & Ghisi (2021) and Maskwa et al. (2021), the adoption of these systems must be understood as an essential strategy of adaptation to climate change. Limiting the implementation of these systems to purely economic criteria will compromise their potential to transform, and will perpetuate decision-making that is out of step with the urgency of the current environmental scenario. The inclusion of environmental and social indices in the decision-making process will clearly be more effective as a strategy for the revelation of the true value of these systems, and should also encourage their more widespread adoption in urban environments.

4. CONCLUSIONS

The present study identified the principal factors determining the environmental and economic performance of IRGR systems in private residences: (i) the intensive use of recycled water; (ii) the use of renewable energy sources, and (iii) the integration of storage, treatment, and distribution of rain and greywater.

The LCA indicated that the operational phase has the most impact, due to its power demands. However, the alternative scenario – which had a greater demand for recycled water and the use of solar power – reduced the impacts by more than 50% per cubic meter of recycled water, with a better performance in all the categories of the ReCiPe method, even when the impacts of the solar power infrastructure are taken into account.

The alternative scenario was also the most effective in economic terms, with more rapid returns on investments, greater accumulated savings, and increased viability, reflecting the potential of the synergy between water re-use and renewable energy for urban sustainability. The mean saving of 40% in the consumption of mains water over the course of the year reinforces the efficiency of the hybrid system under real-life conditions, including the dry season.

Strategies for the repair and reconditioning of the most critical components of the system, in particular the pumps, are proposed, with the aim of mitigating the environmental impacts of maintenance, by excluding the upstream effects of manufacturing and logistics. This approach can extend the operational lifespan of the machinery, while reducing waste, and aligning with the principles of the circular economy.

The results of the present study have demonstrated that the performance of decentralized systems, such as the IRGRS, can be improved through operational adjustments and its adaptation to the actual conditions of use. These findings support the development of specific normative guidelines for the regulation and operation of the systems in urban areas. It is hoped that the results of this study will contribute to the formulation of the guidelines necessary for the adaptation of urban planning to climate change, as well as supporting the use of technologies such as IRGRS through government incentives, including fiscal incentives and subsidized tariffs, lines of credit based on performance, and the inclusion of systems of this type in programs of environmental certification for buildings.

Future studies should focus on the assessment of these systems in different climatic, socioeconomic, and constructive contexts. It would also be insightful to include social indices and multicriterion analyses, incorporating aspects such as social acceptance, the perceptions of the consumers of different social groups, regions or income levels. Comparative studies of treatment technologies and the integrated assessment of urban ecosystem services — such as the control of flooding, the regulation of microclimates, and the promotion of biodiversity — represent promising paths for the qualification of decision making and the development of more sustainable urban solutions.

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CONSIDERAÇÕES FINAIS

A presente tese evidenciou que a integração de tecnologias descentralizadas para captação/coleta, armazenamento, tratamento e reúso de águas pluviais e cinzas em ambientes urbanos representa uma alternativa tecnicamente viável e ambientalmente estratégica para enfrentar o crescente estresse hídrico em regiões de clima tropical, especialmente no Centro-Oeste brasileiro. Os resultados do Capítulo 1 demonstraram, por meio de revisão sistemática, que sistemas híbridos de reúso ainda são incipientes na literatura internacional, embora apresentem elevado potencial para aumentar a resiliência hídrica de edificações. Ademais, a maior parte dos sistemas estudados é, de fato, híbrida, ou seja, compartilha o mesmo reservatório de armazenamento e as unidades de tratamento com a mistura das águas pluviais e cinzas. Tal lacuna reforça a originalidade da proposta desenvolvida, ao mesmo tempo em que evidencia a urgência de iniciativas que aliem inovação tecnológica, autonomia local de abastecimento e segurança sanitária.

No Capítulo 2, o monitoramento em escala real de um sistema integrado instalado em residência unifamiliar comprovou a capacidade desse tipo de arranjo em reduzir significativamente o consumo de água potável (até 55 %), sem comprometer atributos de qualidade físico-química e microbiológica, desde que sejam ajustados parâmetros operacionais como aeração e desinfecção por radiação UV. A análise de desempenho evidenciou que a otimização contínua desses parâmetros é essencial para garantir a estabilidade do sistema e que estudos futuros podem otimizar seu potencial de amortização de cheias, configurando-se como etapa-chave para a replicação segura da tecnologia em contextos urbanos.

Já no Capítulo 3, a avaliação de ciclo de vida (ACV) comparativa demonstrou que a adoção do sistema integrado promoveu redução de impactos ambientais em múltiplas categorias, com destaque para “mudanças climáticas” e “toxicidade humana” nos cenários de maior demanda e consumo da água reciclada com fonte de energia solar. Apesar do aumento marginal no consumo energético e nas emissões associadas aos componentes de tratamento, os ganhos ambientais e econômicos decorrentes da substituição de água potável compensaram amplamente esses consumos relacionados à operação e manutenção do sistema. Adicionalmente, os resultados da análise econômica sugerem viabilidade de retorno financeiro em médio prazo, especialmente quando a tecnologia é implantada em edificações com elevada demanda por água reciclada ou dotadas de incentivos tarifários.

De forma integrada, os três capítulos atestam a robustez científica, relevância socioambiental e originalidade tecnológica desta tese, a qual culminou no desenvolvimento e registro, junto ao INPI, de uma patente de sistema inovador para reúso descentralizado de águas em ambientes urbanos. Tal inovação reforça o protagonismo da ciência nacional e o papel estratégico das universidades públicas no desenvolvimento de soluções que respondam aos desafios emergentes das cidades do futuro — mais resilientes, regenerativas e circulares. Conclui-se que sistemas integrados de reciclagem de águas pluviais e cinzas, como o aqui proposto, constituem estratégia promissora para ampliar a segurança hídrica e climática, contribuindo diretamente para a adaptação às novas condições hidrometeorológicas extremas e com elevado potencial de replicação no contexto urbano do Centro-Oeste brasileiro. Recomenda-se, como continuidade, o aprofundamento de estudos de aceitabilidade social e institucionais, bem como o desenvolvimento de ferramentas de gestão inteligente do reservatório que incorporem automação, esvaziamento controlado e algoritmos preditivos de uso como elementos-chave de aprimoramento da tecnologia proposta.

SUPPLEMENTARY MATERIAL

Chapter I

Table S1. Characteristics and configurations of the combined RWH-GWR systems described in the 41 papers selected for analysis in the present study.

Reference[a]	Locality / Köppen-Geiger climate category	Scale / Occupants[b]	Greywater collections[c]	Roof area (m^2)	Treatment systems[d]	Storage capacity (m^3)[e]	End uses[f]
Dixon et al. (1999)[S]	London, UK/Cfb	SH / 1–5	Bth, Sh, Wb, Wm	20, 40, 60	–	RS 0-2, GS 0-0.3	RW&GW Tf
Smith et al. (2000)[C]	London, UK/Cfb	C (Millennium Dome) / up to 120,000	Wb	100,000 (up to 100 m^3/d)	RW first flush, wetland; GW BAF; RW&GW UF, RO, disinfection	–	RW&GW Tf, Uf
Birks et al. (2004)[C]	London, UK/Cfb	C (Millennium Dome) / up to 120,000	Wb	100,000 (up to 100 m^3/d)	RW first flush , wetland; GW BAF; RW&GW UF, RO, disinfection	–	RW&GW Tf, Uf
Ghisi and Ferreira (2007)[C]	Florianópolis, Brazil / Cfa	GH / ~39.7	Sh, Wb, Wm	324	GW wetland	RS 10, 3; GS 2	RW Wm, Tf; GW Tf
Ghisi and Oliveira (2007)[C]	Palhoça, Brazil / Cfa	SH /~2.5	Sh, Wb, Wm	208.1	GW wetland	RS ~4, 0.25; GS 0.25	RW Wm, Tf; GW Tf
Kim et al. (2007)[LS]	Jeju, South Korea / Cfa	–	Sh, Wb	–	RW FFM; RW, GW, RW&GW MM	–	–
Zhang et al. (2009)[C, S]	Melbourne, Australia / Cfb	GH, C / 176	Sh, Wb	~750	GW disinfection, filtration	RS ~42.5; GS 5	RW Tf; GW Wm, Tf, Ou; RW&GW Wm, Tf, Ou
Zhang et al. (2010)[C, S]	Cranbrook, Australia / BSk	GH / 270; SH / ~2,4	Sh, Wb, Wm, Ks	249	RW filter, ST; GW MBR, disinfection	RS 12, 30; GS 3	RW, GW Tf, Ir
Hu and Zhang (2012)[LS]	United States / Af	–	synthesized greywater	–	GW STB, MBR	–	–
Castleton et al. (2014)[C]	United Kingdom / Cfb	O / up to 1,000	Sh, Wb	140	RW&GW ST, MMF, desinfection	RS&GS 8	RW&GW Tf, Uf

Table S1. Characteristics and configurations of the combined RWH-GWR systems described in the 41 papers selected for analysis in the present study (*Continued*).

Reference[a]	Locality / Köppen-Geiger climate category	Scale / Occupants[b]	Greywater collections[c]	Roof area (m^2)	Treatment systems[d]	Storage capacity (m^3)[e]	End uses[f]
Stec and Kordana (2015)[C]	Warsaw, Poland / Dfb	GH / 1,730,000	Sh, Wb, Wm	500	GW ST, UF, biological processes	RS 16; GS 3, 4	RW Tf; GW Tf; RW&GW Tf, Ir, Fc
Ghisi et al. (2014)[C, S]	Florianópolis, Brazil / Cfa	S	Wm, Wb	800	_	RS, RS&GS 22, 5	RW, GW, RW&GW Tf, Uf, Fc
Stratigea and Makropoulos(2015)[S]	Athens, Greece / Csa	C (National Gallery) / 1,095 per day	Sh, Wb	1963 (variant 40% green roof)	_	Green roof & GS 70; RS&GS 200	Green roof & GW, RW Tf, Ir; RW&GW Tf
Bapat et al. (2016)[C]	Nagpur, India / As	GH / 448 homes	Bh, Sh, Wb, Wm	5,277.63	RW Coarse filter, first flush; GW ST, MMF, wetland, GAC, broken brick	_	RW Ir, Ou; GW Tf
Vieira and Ghisi (2016)[S]	Florianópolis, Brazil / Cfa	GH (low income)	Sh, Wb, Wm	56-122	RW first flush, UV desinfection; GW ST, wetland, UV desinfection	RS 3.1	RW Wm; GW Tf
López Zavala et al. (2016)[C]	Monterrey, Mexico / Am	U / 20,000	Sh, Wb	65.768,75	RW first flush, GOT, deep bed filters; GW SNTS; RW&GW disinfection	RS&GS 306-2006	RW&GW Tf, Uf, Fc, Ir, Frc
Aybuğa and Işildar (2017)[S]	Ankara, Turkey / Csb	SH / 4	(1) Sh, Wb, Wm; (2) Sh, Wb, Wm, Ks, Dw	(1) 200; (2) 250	_	RS 6-18; GS 0.18, 0.22	RW (1) Wm, Dw; (2) Wm, DW, Ir; GW Tf
Domínguez et al. (2017)[C]	Bucaramanga, Colombia / Af	GH (low income) / 1593 homes	Sh, Wb	~30,5/home	RW SCF, first flush; GW (reused within 24 h)	RS 0.5 (no network); GS 0.25 (located 1.7 m from the floor)	RW multiple uses; GW Tf
Leong et al. (2018b)[C]	Selangor and Penang, Malaysia / Af	R, O, C, S	R Sh, Wb, Wm; O, C, Sk, Wb	R 536; O 2,283; C 37,200; S 1,828	RW (S) first flush; GW MMF, GAC filter; RW&GW (S) O_3	R (RS, GS) 8; O (RS, RS&GS) 55.5; C (RS) 412; S (RS) 1, 36	RW, GW, RW&GW Tf, Wm, Ir

Table S1. Characteristics and configurations of the combined RWH-GWR systems described in the 41 papers selected for analysis in the present study (*Continued*).

Reference[a]	Locality / Köppen-Geiger climate category	Scale / Occupants[b]	Greywater collections[c]	Roof area (m^2)	Treatment systems[d]	Storage capacity (m^3)[e]	End uses[f]
Stec et al. (2017)[C]	Rzeszow, Poland / Cfb	SH/ 4	Sh, Wb	150	GW biological and UF	2.65	RW, GW, RW&GW Tf, Ir
Leong et al. (2018a)[C]	Petaling and Sepang, Malaysia / Af	C, R	C Wb; R Sh, Wb, Wm	C 2477; R 487	RW&GW MMF, GAC, O_3	C GS 1.4; R RS&GS 3.6	GW, RW&GW Ir
Marinoski et al. (2018)[C]	Palhoça, Brazil / Cfa	20 SH (low income) / 60	Sh, Wb	80/SH	GW wetland	RS 3, 0.25; GS 0.1	RW Tf, Wm, Ou; GW Tf
Markovič (2018)[C]	Košice, Slovakia / Dfb	U / 60	Wb	_	_	RS 3.5; GS 0.3	RW Tf, Ir; GW Tf
Oviedo-Ocaña et al. (2018)[C]	Bucaramanga, Colombia / Af	SH / 4	Sh	101	RW leaf filter, coarse filter, first flush, SCF; GW sandbox, ST, SSF	RS 2.2; GS 0.3	RW Wm, S, Ou; GW Tf
Wanjiru and Xia (2018)[S]	Pretoria, South Africa / Cfa	SH	Sh, Wm	50	RW filter; RW&GW UV	GS 0.4; RS&GS 0.2	RW&GW Tf, Ir
Leong et al. (2019)[C]	Petaling and Sepang, Malaysia / Af	C, R	C Wb; R Sh, Wb, Wm	C 177; R 410	RW O_3; GW, RW&GW sand filter, GAC, O_3	C (GS) 1.4; R (RS&GS) 3.6	RW, GW, RW&GW Tf, Ir
Marinoski and Ghisi (2019) [C]	Florianópolis, Brazil / Cfa	SH (low income) / 4	Sh, Wb, Wm	59–78	RW first flush; GW wetland, desinfection	RS 5, 0.15; GS 0.25	RW Ir, Fc, Ou, Wm; GW Tf
Zanni et al. (2019)[C]	Bologna, Italy / Cfb	SH/ 3; GH/ 27	Bh, Sh, Wb, Wm	SH 150; GH 400	RW UF, UV, Cl; GW filter (shard of tile), UF, Aeration	RS SH 2-4, GH 18-42; GS 1	RW Tf, Ir; GW Tf
Rosa and Ghisi (2020)[C]	Florianópolis, Brazil / Cfa	SH / 4	Wm	120	_	RS 5; GS 0.5	RW Wm; GW Tf
Alarcon et al. (2021)[C]	Cusco, Peru / Cwb	GH / 44	Sh, Wb	100	RW filter; GW MBR, decantation, disinfection	_	RW Wm; GW Tf, Fc

Table S1. Characteristics and configurations of the combined RWH-GWR systems described in the 41 papers selected for analysis in the present study (*Continued*).

Reference[a]	Locality / Köppen-Geiger climate category	Scale / Occupants[b]	Greywater collections[c]	Roof area (m^2)	Treatment systems[d]	Storage capacity (m^3)[e]	End uses[f]
Chen et al., 2021[C]	Fukuoka, Japan / Cfa	U	Sh, Wb, Ks	1,109-35,060	RW filter; GW MMF, MBR, O_3 , Cl	RS 640; GS 380	RW Ir, Co, Frc, Ou; GW Tf
Maskwa et al. (2021)[S]	12 cities in the United States / Af	SH/ 3, GH/ 15 typical	Sh, Wb, Wm	SH 116, GH 427	RW simple filter, GW MBR	GH (RS) 5-10 m^3, SH (RS) 4-6 m^3; GH (GS) 2–3 m^3	RW, GW Tf, Ir
Rosa and Ghisi (2021)[C]	Florianópolis, Brazil / Cfa	SH / 4	Wm	120	RW first-flush, disinfection; GW filtration, desinfection	RS 4 and 1; GS 0.5	RW Wm, GW Tf
Stang et al. (2021)[S]	Boston, United States / Dfa	SH/ 3, GH/ 15 typical	Sh, Wb, Wm	_	RW, GW filtration	average RS 0.94; GS 1.7	RW, GW Tf, Ir
Zhang et al. (2021) [S]	Durban, South Africa / Cfa	SH	Sh, Wm	100	GW BioMembrane (DeHoust GWM)	RS&GS 1.5, 1 (upper)	RW&GW Tf, Ir
Chen et al. (2022)[C,S]	20 cities in Japan / Dfb, Dfa, Cfa	Buildings	Sh, Wb	_	RW first-flush or filtration; GW filtration, desinfection	_	RW Co, Ir,Ou; GW Tf; RW&GW Co, Ir, Ou, Tf
Gómez-Monsalve et al. (2022)[C]	Bucaramanga, Colombia / Af	SH / 4	Sh	101	RW leaf filter, coarse filter, first flush, SCF; GW sandbox, ST, SSF	RS 2.2; GS 0.3	RW Wm, S, Ou; GW Tf

[a] C = Case study, S = Simulation, LS = Laboratory scale;
[b] SH = Single House; GH = Group of Houses; R = Residence; C = Commercial building; O = Office building; U = University; S = School;
[c] Bh = Bath; Sh = Shower; Wb = Wash basin; Wm = Washing machine; Ks = Kitchen sink; Sk = Sink; Dw = Dishwasher;
[d] RW = Rainwater; GW = Greywater; BAF = Biological Aerated Filter; FFM = Fiber Filter Media; MFF = Multimedia Filter; GAC = Granular Activated Carbon filter; SCF = Self-Cleaning Filter; SSF = Slow Sand Filter; STB = Shredded Tire Biofilter; UF = Ultrafiltration; RO = Reverse Osmosis; MM = Metal Membrane; MBR = Membrane Bioreactor; Cl = Free residual Chlorine; ST = Sedimentation Tank; GOT = Grease and Oil Trap; SNTS = Soil Natural Treatment System; O_3 = Ozone disinfection; UV = Ultraviolet disinfection.
[e] RS = Rainwater storage; GS = Greywater storage; RS&GS = Combined rain and grey water storage;
[f] Tf = Toilet flush; Uf = Urinal flush; Ir = Irrigation; Fc = Floor cleaning;Ou = Outdoor use; Frc =Fire control; Co = Cooling.

Table S2. Overview of the data on the methods used for sizing storage tanks described in the 41 papers selected for analysis in the present study.

Reference	Rainfall data	Method / Tool	Total water demand
Dixon et al. (1999)	One year hourly time-series	Water mass balance (YBS algorithm) / Monte Carlo	61.3–126.4 L per capita/day
Smith et al. (2000)	_	_	43,200.0 m^3/year
Birks et al. (2004)	_	_	43,200.0 m^3/year
Ghisi and Ferreira (2007)	Daily, historical	Water mass balance / Netuno	151.3 L per capita/day
Ghisi and Oliveira (2007)	Daily, historical	Water mass balance / Netuno	175.1 L per capita/day
Zhang et al. (2009)	Daily, historical	Water mass balance / UVQ (Urban Volume and Quality)	10.0 L per capita/day
Zhang et al. (2010)	Daily, historical	Water balance / AQUACYCLE	181.0 L per capita/day
Castleton et al. (2014)	One year hourly time-series	_	2,053.0 m^3/year
Ghisi et al. (2014)	Daily, historical	Water mass balance / Netuno	_
Stec and Kordana (2015)	Daily, historical	Water mass balance	68.3 L per capita/day
Stratigea and Makropoulos (2015)	Daily, historical	Water mass balance	_
Bapat et al. (2016)	_	Sustainable renewable resource management (SRRM)	180.0 L per capita/day
Vieira and Ghisi (2016)	Daily, historical	Water mass balance / Netuno	122.9 L per capita/day
López Zavala et al. (2016)	Daily, historical	Water mass balance	178139.3 m^3/year
Aybuğa and Işildar (2017)	Daily, historical (converted to weekly totals)	Water mass balance / Ripple Method	211.0 L per capita/day
Domínguez et al. (2017)	Daily, historical (converted to weekly totals)	Water mass balance	130.0 L per capita/day
Gómez-Monsalve et al. (2022)	Daily, historical (converted to weekly totals)	Water mass balance	>203.0 L per capita/day

Table S2. Overview of the data on the methods used for sizing storage tanks described in the 41 papers selected for analysis in the present study (*Continued*).

Reference	Rainfall data	Method / Tool	Total water demand
Leong et al. (2018b)	Daily, historical	Water mass balance / RainTANK model (YAS algorithm)	234.0 L per capita/day
Stec et al. (2017)	Daily, historical	Water mass balance / (simulation model)	48.0 L per capita/day
Marinoski et al. (2018)	Daily, historical	Water mass balance / Netuno	128.3 L per capita/day
Markovič (2018)	Thomson weir (flow calculated *in loco*)	Water mass balance	10.0 (greywater)
Oviedo-Ocaña et al. (2018)	Daily, historical (converted to weekly totals)	Water mass balance	>203.0 L per capita/day
Wanjiru and Xia (2018)	Daily, historical	Water mass balance	_
Leong et al. (2019)	Daily, historical	Water mass balance / RainTANK model (YAS algorithm)	–
Marinoski and Ghisi (2019)	Daily, historical	Water mass balance / Netuno	159.0 L per capita/day
Zanni et al. (2019)	Daily, historical	Water mass balance/ EPA SWMM	140.0 L per capita/day
Rosa and Ghisi (2020)	Daily, historical	Water mass balance / Netuno	147.6 L per capita/day
Alarcon et al. (2021)	Daily, historical	Water mass balance / MHS1 (Sustainable Hydrology Model)	137.0 L per capita/day
Chen et al. (2021)	Daily, historical	Water mass balance (YBS, YAS algorithms)	32,844.0 m^3/year
Maskwa et al. (2021)	Daily, historical	Water mass balance (YAS algorithms)	215.0 L per capita/day
Rosa and Ghisi (2021)	Daily, historical	Water mass balance / Netuno	148.0 L per capita/day
Stang et al. (2021)	Daily, historical	Water mass balance (YAS algorithms) / Brent's method	181.0 L per capita/day
Zhang et al. (2021)	5 year hourly time-series	Mixed integer linear programming model	_
Chen et al. (2021)	Daily, historical	Water mass balance (YBS, YAS algorithms)	_

Chapter III

Table S1 – Initial costs for construction materials.

Component	Amount	Unit	Unit cost (R$)	Total cost (R$)
Rain collection pipe PVC 100mm 6m	1	unit	R$ 287.00	R$ 287.00
Ball Valve PVC 100mm	5	m	R$ 54.17	R$ 270.85
Greywater collection pipe PVC 50mm 6m	1	unit	R$ 339.80	R$ 339.80
Tank HDPE 1 m³(Wetland)	0.8	m³	R$ 96.00	R$ 76.80
Gravel #0 e #1	10	unit	R$ 30	R$ 300.00
Dwarf Papyrus seedlings	10	unit	R$ 30	R$ 300.00
Storage tank HDPE 5 m³	1	unit	R$ 2,636.90	R$ 2,636.90
Cement (reinforced concrete 1.5m³): 300 kg/m³	450	kg	R$ 225.00	R$ 1,455.00
Sand (reinforced concrete 1.5m³) 600 kg/m³	900	kg	R$ 60.00	
Gravel #1 (1.5m³ reinforced concrete): 1000 kg/m³	1500	kg	R$ 120.00	
Steel (reinforced concrete 1.5m³): 70 kg/m³	105	kg	R$ 1,050	
Aeration pump 45W 2500 L/h	1		R$ 227.05	R$ 227.05
Booster pump 450W 700 L/h	1	unit	R$ 413.90	R$ 413.90
Solenoid Valve Normal Closed	1	unit	R$ 179.90	R$ 179.90
Level buoys electrical 5A	4	unit	R$ 142.90	571.6
Supply tank HDPE 1 m³	1	unit	339.8	R$ 339.80
Bracket-Mounted Filter PP	1	unit	303.91	R$ 303.91
Cartridge Filter PP 5µm	3	unit	R$ 65.04	R$ 195.12
UV Lamp 11W Nominal Lifespan: 8766h for water tanks from 1,000 liters	1	unit	R$ 300.00	R$ 300.00
UV Auxiliary Pump 8W 530L/h	1	unit	R$ 98.00	R$ 98.00
Total component cost (R$)				R$ 8,295.63

Table S2 – Initial costs related to labor.

Description	Hours worked	Hourly cost (R$)	Total cost (R$)
Installation (piping, underground tank and reinforced concrete (3 days of 8 hours each)	24	R$ 25	R$ 600
Wetland Installation	5	R$ 25	R$ 125
Excavation with machine to allocate the underground tank	1.5	R$ 180	R$ 270
Electrical installation (solenoid, pumps, floats, UV)	8	R$ 35.00	R$ 280
Total cost (R$)			R$ 1,275

Table S3. Environmental impact assessment results for the combined system using the ReCiPe (H) method in OpenLCA.

Scenario	Indicator	Construction	Maintenance	Solar operation	Grid Mix Operation	Unit
Baseline	Climate change	4.20E-01	2.44E-01	6.40E-01	2.28E+00	kg CO$_2$-Eq
	Fossil depletion	1.63E-01	1.01E-01	1.93E-01	5.50E-01	kg oil-Eq
	Freshwater ecotoxicity	7.96E-03	1.04E-02	2.20E-01	1.23E-02	kg 1,4-DCB-Eq
	Freshwater eutrophication	1.01E-04	9.81E-05	4.64E-04	2.79E-04	kg P-Eq
	Human toxicity	1.27E-01	6.68E-01	6.55E-01	6.56E-01	kg 1,4-DCB-Eq
	Ionising radiation	1.42E-02	1.33E-02	6.26E-02	2.46E-01	kg U235-Eq
	Marine ecotoxicity	7.36E-03	1.01E-02	1.95E-01	1.02E-02	kg 1,4-DCB-Eq
	Marine eutrophication	4.72E-04	2.99E-04	8.81E-04	2.61E-03	kg N-Eq
	Metal depletion	9.64E-02	4.94E-02	2.29E-01	2.51E-02	kg Fe-Eq
	Natural land transformation	6.13E-05	3.18E-05	1.25E-04	3.20E-03	m^2
	Ozone depletion	8.05E-07	1.28E-08	7.74E-08	1.31E-07	kg CFC-11-Eq
	Terrestrial acidification	1.69E-03	1.31E-03	3.05E-03	1.12E-02	kg SO$_2$-Eq
	Water depletion	3.96E-03	6.49E-04	3.99E-03	6.60E-03	m^3

Scenario	Indicator	Construction	Maintenance	Solar operation	Grid Mix Operation	Unit
Alternative	Climate change	1.20E-01	1.03E-01	2.52E-01	8.99E-01	kg CO$_2$-Eq
	Fossil depletion	4.68E-02	5.35E-02	7.62E-02	2.17E-01	kg oil-Eq
	Freshwater ecotoxicity	2.28E-03	3.57E-03	8.66E-02	4.87E-03	kg 1,4-DCB-Eq
	Freshwater eutrophication	2.88E-05	3.42E-05	1.83E-04	1.10E-04	kg P-Eq
	Human toxicity	3.65E-02	1.97E-01	2.58E-01	2.59E-01	kg 1,4-DCB-Eq
	Ionising radiation	4.08E-03	4.85E-03	2.47E-02	9.71E-02	kg U235-Eq
	Marine ecotoxicity	2.11E-03	3.40E-03	7.68E-02	4.04E-03	kg 1,4-DCB-Eq
	Marine eutrophication	1.35E-04	1.17E-04	3.47E-04	1.03E-03	kg N-Eq
	Metal depletion	2.76E-02	1.54E-02	9.02E-02	9.90E-03	kg Fe-Eq
	Natural land transformation	1.76E-05	1.25E-05	4.93E-05	1.26E-03	m^2
	Ozone depletion	2.31E-07	5.00E-09	3.05E-08	5.15E-08	kg CFC-11-Eq
	Terrestrial acidification	4.83E-04	4.84E-04	1.20E-03	4.43E-03	kg SO$_2$-Eq
	Water depletion	1.13E-03	2.28E-04	1.57E-03	2.61E-03	m^3

Table S4. Comparison of economic indicators found in the literature for integrated systems.

Reference	Characteristics systems	Cost indicator:		
		Net Present Value, USD	**Payback in years**	**Internal Rate of Return, % per annum (except when specified)**
Present study	SH ^{Bs}(2 residents) ^{As}(4 residents + pool); Roof area = 203.47 m²; Storage: RW&GW = 5 m³	^{Bs}(solar) $4,947.96; ^{Bs}(Grid) $1,573.54; ^{As}(solar) $**21,807.96;** ^{As}(Grid) $17,146.07 (TMA 3%)	^{Bs}(solar): 24; ^{Bs}(grid): 40; ^{As}(solar): **8**; ^{As}(grid): 12	IRR (50): ^{Bs}(solar) 7.96%; ^{Bs}(grid): 4.71%; ^{As}(solar) **17.72%;** ^{As}(grid) 13.96%
Ghisi and Oliveira, 2007	SH (~2.5 residents); Roof area = 208.1 m²; Storage: RW = 4 m³; GW = 0.25 m³	-	Mean 60	-
Ghisi and Ferreira, 2007	MH (~39.7 residents); Roof area = 324 m²; Storage: RW = 10 m³, 3 m³; GW = 2 m³	-	Mean 5.7	-
Ghisi et al., 2014	Roof area = 800 m²; Storage: RW&GW = 5 m³	$34,724,02 (TMA = 0.68% per month)	Discounted payback 1.8	5.37% per month
Zavala et al., 2016	University (20,000 occupants); Roof area = 65.768,75 m²; Storage: RW&GW = 306–2006 m³	$50,483.2 (TMA = 3%)	_	IRR (6): 4.6%
Domínguez et al., 2017	GH (1593 residents); Roof area: ~30.5 m² per residence; RW = 0.5 m³; GW = 0.25 m³	$337.0 (TMA = 3.51%)	30	IRR (50): 4.69%
Oviedo-Ocaña et al., 2018	SH (4 residents); Roof area = 101 m²; Storage: RW = 2.2 m³; GW = 0.3 m³	$4,053.0 (TMA = 4.05%)	23	IRR (50): 6.5%
Rosa and Ghisi, 2020	SH (4 residents); Roof area = 120 m²; Storage: RW = 5 m³; GW = 0.5 m³	$1,958.67 (TMA = 0.60% per month)	5.3	1.99% per month
Zhang et al., 2021	SH; Roof area = 100 m²; Storage: RW&GW = 1.5 m³	-	Discounted payback 4.4	-
Rosa and Ghisi, 2021	SH (4 residents); Roof area = 120 m²; Storage: RW = 4 m³; GW = 0.5 m³	$759.60 (TMA = 0.60% per month)	9.5	1.23% per month
Alarcón et al., 2021	MH (44 residents); Roof area =100 m²; Storage: unspecified	-	11.0	-

Note: RW = Rainwater; GW = Greywater; RW&GW = mixed rainwater and greywater; SH = Single-Family Household; MH = Multifamily Housing; Bs = Baseline scenario; As = Alternative scenario.

Table S5. Monthly values related to potable water savings between the scenarios.

Scenario	**Month**	**Recycled water consumption (m^3/month)**	**Potable water consumption (m^3/month)**	**Total consumption (m^3/month)**	**Water savings (%)**	**Amount saved (R$/month)**
Baseline	Feb	4.05	6.75	10.80	**37.52**	R$ 42.77
	Mar	4.37	6.83	11.19	**39.01**	R$ 46.09
	Apr	2.31	6.57	8.88	**26.01**	R$ 24.39
	May	3.45	8.46	11.91	**28.97**	R$ 36.43
	Jun	3.49	4.31	7.80	**44.74**	R$ 36.85
	Jul	4.62	6.34	10.96	**42.15**	R$ 48.79
	Aug	5.77	6.51	12.28	**46.99**	R$ 60.93
	Sep	3.94	6.67	10.61	**37.13**	R$ 41.61
	Oct	5.47	7.90	13.37	**40.91**	R$ 57.76
	Nov	3.57	5.98	9.55	**37.38**	R$ 37.70
	Dec	3.36	3.50	6.86	**48.98**	R$ 35.48
	Jan	3.08	3.70	6.78	**45.43**	R$ 32.52
Alternative	Feb	20.22	16.19	36.41	**55.53**	R$ 213.48
	Mar	18.69	16.04	34.73	**53.82**	R$ 197.40
	Apr	3.50	26.02	29.52	**11.86**	R$ 36.96
	May	6.27	29.31	35.58	**17.63**	R$ 66.21
	Jun	5.25	22.10	27.35	**19.19**	R$ 55.42
	Jul	6.25	27.42	33.67	**18.55**	R$ 65.96
	Aug	6.40	29.12	35.52	**18.02**	R$ 67.57
	Sep	5.78	27.20	32.98	**17.54**	R$ 61.07
	Oct	22.70	15.79	38.49	**58.97**	R$ 239.69
	Nov	18.89	11.95	30.84	**61.25**	R$ 199.44
	Dec	18.47	7.00	25.47	**72.53**	R$ 195.06
	Jan	17.90	7.40	25.31	**70.75**	R$ 189.07

Note: roof area 203,47 m^2; Storage: RW&GW 5 m^3; Baseline scenario: single-family house (2 residents); Alternative scenario: single-family house (4 residents + pool).