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Techno-economic assessment and system-level comparison of construction demolition waste-derived stormwater filter media with conventional alternatives

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ABSTRACT

The increasing demand for sustainable stormwater treatment systems has intensified interest in low-cost and circular filtration materials capable of reducing both environmental burden and long-term operational cost. This study presents an integrated techno-economic assessment (TEA) framework to evaluate construction and demolition waste (CDW)-derived filtration media for decentralized stormwater treatment and benchmark their performance against conventional filtration materials, including expanded clay, processed clay, and biochar, under harmonized Nordic operating conditions while explicitly incorporating circular end-of-life recovery scenarios. The assessment was conducted using consistent system boundaries, operational assumptions, and a 50-year functional lifetime. Key techno-economic indicators, including Net Present Cost (NPC), levelized cost of treatment (LCOT), and cost per unit contaminant removed, were evaluated together with sensitivity analysis for operational and economic uncertainties. Under the harmonized base-case assumptions, CDW-derived filtration media achieved approximately 19–70% lower NPC and LCOT than the conventional benchmark materials, depending on the end-of-life pathway and benchmark considered. Recycling and reuse further improved the economic competitiveness of the CDW system through avoided disposal costs and recovered-value credits. Because comprehensive long-term field-performance data for the CDW-derived medium are not yet available, its long-term technical performance was evaluated using scenario-based ranges derived from available experimental observations and benchmark data, with the associated uncertainty examined through sensitivity analysis. Although processed clay and expanded clay showed higher contaminant-removal efficiencies for Cu, Zn, and Pb, CDW-derived media provided a competitive balance between treatment performance, economic feasibility, and circularity potential. Sensitivity analysis identified operating expenditure (OPEX), maintenance interval, and replacement frequency as the dominant factors influencing long-term economic performance. Overall, the findings indicate that CDW-derived filtration media represent a promising circular and economically attractive alternative for decentralized stormwater treatment applications, particularly under Nordic conditions. Future research should focus on long-term pilot-scale validation, hydraulic and clogging behavior, freeze–thaw durability, and integrated environmental life-cycle assessment to further strengthen the practical applicability of CDW-based filtration systems.

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1. Introduction

Rapid industrialization, population growth, and urbanization are giving rise to increasingly impervious land surfaces in urban areas (Hossain et al., 2012; Li et al., 2019; He et al., 2021; Kumar et al., 2024). The intensifying impacts of urbanization have significantly altered natural hydrological cycles, leading to increased volumes and peak intensities of stormwater runoff in urban environments (Li et al., 2019; Patterson and Haught, 2021). The expansion of infrastructure surfaces such as roads, roofs, and pavements reduces natural infiltration and accelerates the transport of contaminants into receiving water bodies (Rodak et al., 2019; Tabari, 2020; Zhou et al., 2022; Kumar et al., 2020; Müller et al., 2020; Ferdowsi et al., 2024). Consequently, stormwater has become a major diffuse source of pollution, carrying heavy metals such as copper (Cu), zinc (Zn), and lead (Pb), along with nutrients including phosphorus (P) and nitrogen (N), and total suspended solids (TSS), all of which pose serious risks to aquatic ecosystems and water quality (Göbel et al., 2007; Barbosa et al., 2012; McGrane, 2016; Paule-Mercado et al., 2016; Liu et al., 2016; Rodak et al., 2019). These pollutants contribute to eutrophication, toxicity in aquatic organisms, and long-term degradation of surface and groundwater systems (Conley et al., 2020; Soltaninia et al., 2022; Lancaster et al., 2024). In cold-climate regions such as the Nordics, additional challenges arise due to freeze–thaw cycles, snowmelt-driven runoff pulses, and intermittent flow conditions, which can significantly affect the performance and reliability of conventional centralized treatment systems. As a result, the quality of stormwater runoff is expected to become increasingly critical in the future, potentially compromising the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 6 (Clean Water and Sanitation). Therefore, there is an increasing need for decentralized, cost-effective, and scalable stormwater treatment solutions capable of operating under variable climatic and hydraulic conditions (Fletcher et al., 2015; Lucas et al., 2015; Zhou et al., 2024).

To address these challenges, various filtration-based stormwater treatment media have been developed and widely applied, including lightweight expanded clay aggregate, processed clay products, and carbon-based materials such as biochar (Kalhori et al., 2013, Mlih et al., 2020, Mederos et al., 2024, Garfansa et al., 2025, Omar et al., 2026). These materials have demonstrated effectiveness in removing heavy metals, nutrients, and suspended solids from runoff (Mlih et al., 2020, Mederos et al., 2024, Garfansa et al., 2025). However, their broader implementation is constrained by several practical and environmental limitations. Clay-based media require energy-intensive thermal processing at temperatures approaching 1100–1200 °C, resulting in high embodied energy and associated greenhouse gas emissions (Torabi-Kaveh et al., 2021, Pishdadi-Aghdarreh et al., 2023, Uslu et al., 2024). Biochar, while highly effective for contaminant adsorption, exhibits significant cost variability depending on feedstock and production conditions and is often relatively expensive compared to mineral-based alternatives (Mohan et al., 2014, Ahmad et al., 2014, Ok et al., 2022, Campion et al., 2023, Ahmed et al., 2024, Tang et al., 2025, Ganzi and Pronti, 2026). In addition, these conventional media are subject to logistical and supply-chain constraints, including transportation costs, regional raw material availability, and scalability challenges (Pishdadi-Aghdarreh et al., 2023, Uslu et al., 2024, Tang et al., 2025, Ganzi and Pronti, 2026). Despite their widespread use, there remains limited transparency regarding cost–performance relationships at the system level, which restricts informed decision-making for large-scale or decentralized stormwater treatment implementations (Garbanzos and Maniquiz-Redillas, 2022, Abdeljaber et al., 2022, Liu et al., 2025, Wang et al., 2026). Additionally, the transition toward sustainable urban systems requires not only effective stormwater treatment technologies but also circular resource-management strategies that reduce dependence on virgin materials and minimize waste generation.

In this context, construction and demolition waste (CDW) represents a promising yet underutilized resource for the development of alternative stormwater treatment media. CDW is one of the largest waste streams generated in the European Union (EU) (Moschen-Schimek et al., 2023, Soto-Paz et al., 2023, Munir et al., 2026a). In the EU-27 + 4, approximately 351 Mt of CDW was managed in 2020, with an estimated recovery rate of about 90%; however, approximately 81% of the gross CDW treated was directed to downcycling pathways, indicating that high recovery rates do not necessarily correspond to high-value material circularity (Zhang et al., 2026a). CDW-derived fine fractions possess favorable mineralogical properties and have shown potential for contaminant adsorption in environmental applications (Munir et al., 2026b). From a techno-economic perspective, CDW offers several potential advantages, including low or near-zero feedstock cost, relatively low processing requirements, and widespread local availability, which may reduce transportation and material-production costs (Cudecka-Purina et al., 2024; Munir et al., 2024; da Silva et al., 2026). These characteristics make CDW an attractive candidate for developing circular and cost-effective filtration media for decentralized stormwater treatment systems. Previous studies investigating CDW and other recycled materials for stormwater filtration have largely emphasized material characterization, contaminant-removal performance, and technical feasibility (Bolourieh et al., 2026; Deng et al., 2026; Zhang et al., 2026b; Pitropova et al., 2026), while systematic techno-economic comparisons with conventional stormwater filtration media under harmonized system assumptions remain limited.

Life-cycle costing (LCC) and related economic assessment approaches have been applied to CDW management, recycled aggregate production, and other recycled-material applications, demonstrating that the economic feasibility of CDW valorization can be strongly influenced by processing routes, transportation distance, disposal costs, and end-of-life strategies (Munir et al., 2026a). Economic assessment has also been applied specifically to CDW-derived stormwater filtration, providing initial evidence of the potential cost competitiveness of waste-derived filtration systems (Munir et al., 2026b). However, existing studies generally focus on individual CDW management routes, specific recycled-material applications, or the economic performance of individual filtration systems. Direct material-level comparisons of CDW-derived filtration media with conventional stormwater filtration media under harmonized functional units, system boundaries, service lives, operational conditions, replacement assumptions, and end-of-life scenarios remain limited. Consequently, the relative techno-economic position of CDW-derived media against established filtration alternatives is not yet sufficiently understood.

To address this gap, the present study develops a harmonized techno-economic assessment (TEA) of previously developed CDW-derived filtration media for decentralized stormwater treatment and systematically benchmarks their performance against conventional alternatives, including expanded clay, processed clay, and biochar. A cradle-to-grave framework is applied using consistent system boundaries, functional units, operational assumptions, and a 50-year assessment period. Key decision-making indicators, including net present cost (NPC), levelized cost of treatment (LCOT), and cost per unit of pollutant removed (€/kg), are evaluated together with sensitivity analysis of key operational and economic uncertainties. The unique contribution of this study is therefore the systematic comparison of CDW-derived and conventional filtration media within a common techno-economic framework, enabling their treatment performance, life-cycle cost, and circular end-of-life potential to be evaluated on a consistent basis under Nordic operating conditions.

2. Materials and Methods

2.1. Study framework and approach

The methodological workflow used in this study is presented in Fig. 1a. The assessment comprised selection of filtration media, definition of the functional unit and system boundary, compilation and classification of technical-performance and economic data, harmonization of model inputs, techno-economic modelling, scenario analysis, and sensitivity analysis. Technical-performance evidence was distinguished according to data type and experimental basis, including published flow-through column data for conventional filtration media, preliminary project-scale column data for CDW, and project-specific leaching and stability data for the developed CDW agglomerates.

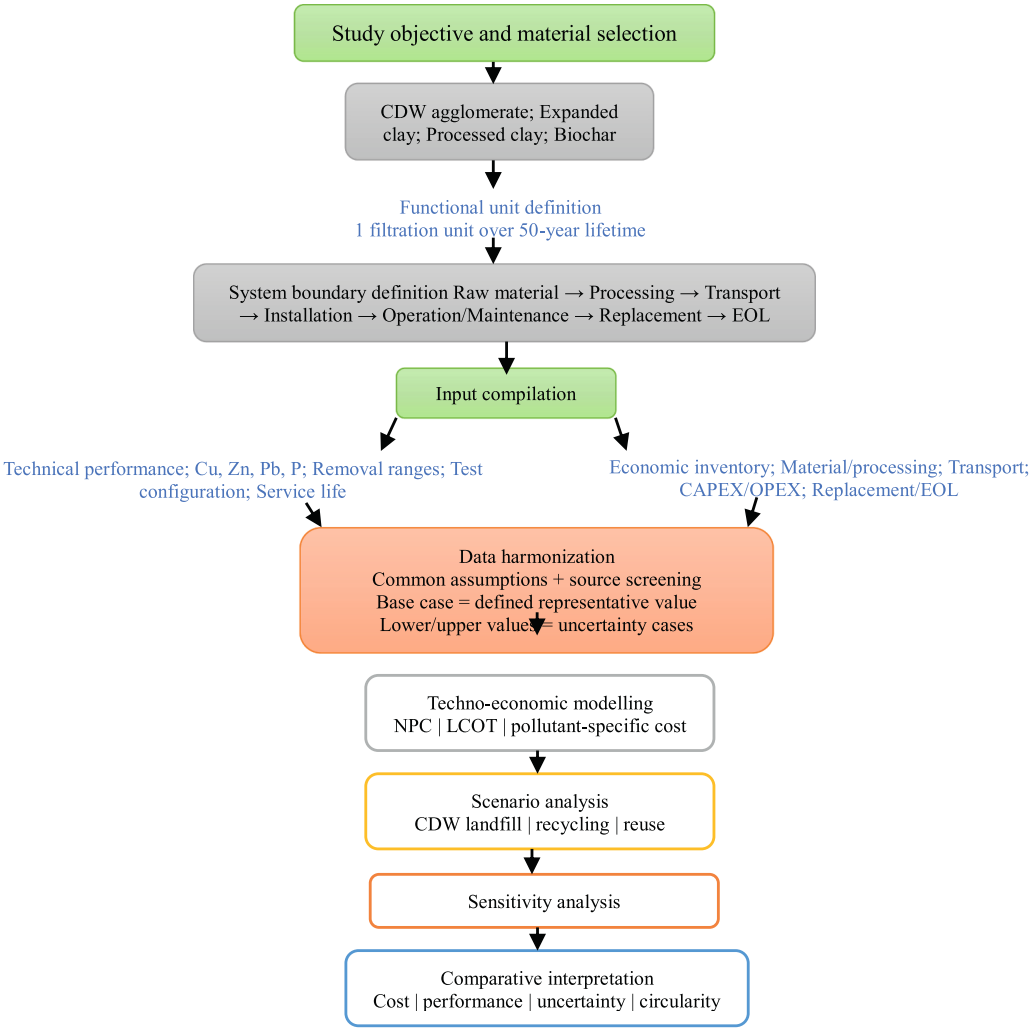


Fig. 1a. Methodological framework of the study: workflow used for technical and economic data compilation, harmonization, techno-economic modelling, scenario analysis, and sensitivity analysis (CAPEX, capital expenditure; OPEX, operating expenditure; EOL, end-of-life).

2.2. Goal, functional unit, and system boundary

The goal of this study was to evaluate the techno-economic competitiveness of CDW-derived filter media for decentralized stormwater treatment and benchmark their performance against conventional filtration materials, including expanded clay, processed clay, and biochar. The assessment aimed to support material selection for Nordic stormwater applications by linking treatment efficiency, operational performance, and life-cycle cost within a harmonized system-level framework.

The functional unit was defined as one decentralized stormwater filtration unit evaluated over a 50-year assessment period. The 50-year period represents the structural and economic analysis horizon of the filtration system rather than the service life of the filtration media, which was modelled separately through replacement assumptions. To facilitate comparison between materials, the results were additionally normalized as levelized cost of treatment (LCOT, €/m³ treated water) and cost per unit of pollutant removed (€/kg).

For the CDW scenario, the reference inventory comprised 15 t of filter material, consistent with the representative full-scale CDW filtration unit previously developed for the Lahti pilot system (Munir et al., 2026b). The annual treated stormwater volume of 500 m³ /year was adopted as a common normalization basis rather than as a site-specific hydraulic design capacity. The value represents the approximate annual runoff generated from a small predominantly impervious urban catchment under Finnish climatic conditions. Finnish climate statistics indicate an annual precipitation magnitude of approximately 600 mm, while the City of Helsinki recommends runoff coefficients of 0.8–0.9 for dense impervious surfaces such as asphalt and concrete (Jokinen et al., 2021; City of Helsinki, 2025). Under these conditions, 500 m³ /year corresponds approximately to runoff from an impervious catchment of about 0.09–0.10 ha. Because the same annual treated volume was applied to all filtration-media alternatives, this assumption affects the absolute LCOT values but not their relative ranking.

A cradle-to-grave system boundary was applied consistently to all evaluated filtration media. The boundary included raw material acquisition or waste collection, material processing, transport to site, filter-unit installation, operation and maintenance, media replacement where required, and end-of-life management through disposal, recycling, or reuse. For the CDW route, crushing, sieving, and low-temperature agglomeration were included, whereas thermal expansion and pyrolysis stages were considered for clay- and biochar-based systems, respectively. Infrastructure external to the filter-media system, such as broader stormwater drainage networks and upstream hydraulic assets, was excluded. The adopted system boundary is illustrated in Fig. 1b. To ensure comparability, common system boundaries, installation assumptions, treated stormwater volume, and assessment period were applied across all alternatives, while material-specific replacement assumptions were evaluated separately.

2.3. Filter media description

Four media alternatives were evaluated: CDW agglomerates, expanded clay, processed clay, and biochar. The CDW medium was conceptualized as a waste-derived agglomerated product produced from collected and sorted CDW fine fractions, and 10–20 vol% plastics. Benchmark materials were represented using technical and economic data obtained from technical documentation and supplier information for expanded clay, processed clay, and biochar. The physical and conceptual characteristics of the evaluated filter

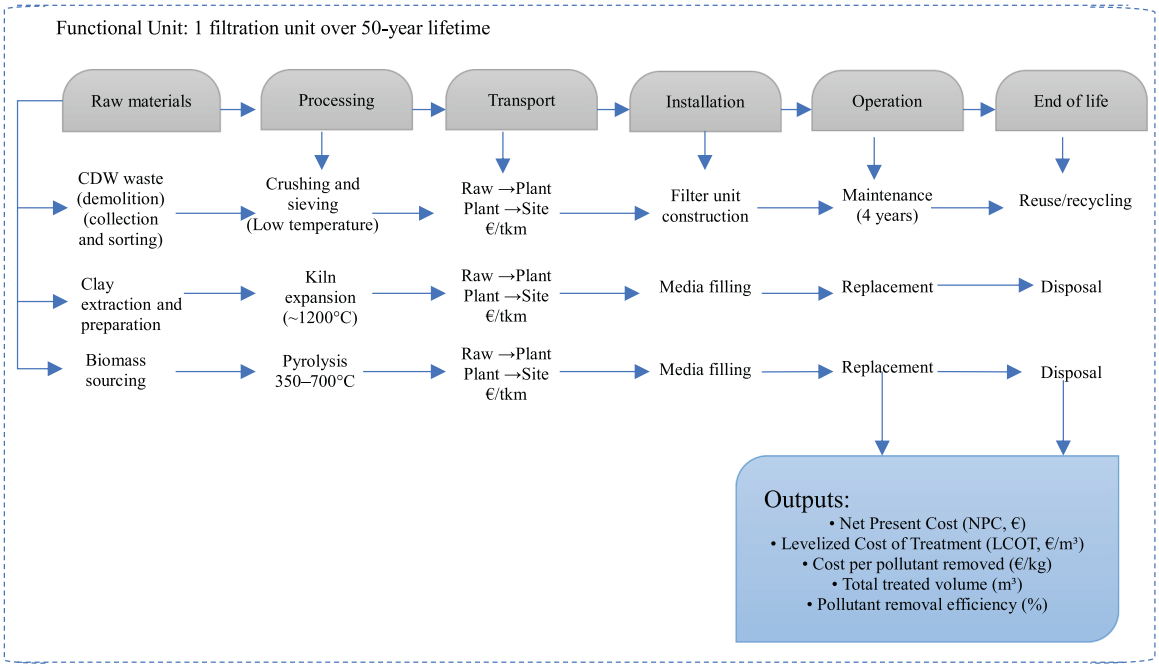


Fig. 1b. Cradle-to-grave system boundary used for the techno-economic comparison of CDW-derived and conventional stormwater filter media.

media are presented in Table 1.

The quantitative comparison was limited to expanded clay, processed clay, and biochar because sufficiently comparable technical and economic data were available for harmonization within the common TEA framework. Other stormwater media, including sand, zeolite, activated carbon, and iron-based sorbents, are also widely used, but differences in system configuration, performance data, service life, and cost basis limit direct comparison (Westholm, 2023).

2.4. Technical performance data

Technical-performance inputs were classified according to their experimental basis and level of validation. For the conventional filtration media, contaminant-removal data were derived primarily from the Finnish StormFilter experimental programme reported by Holt et al. (2018). The StormFilter programme included laboratory flow-through column testing of individual filtration materials using synthetic stormwater, rather than relying solely on short-term batch tests. The experiments were conducted over several weeks and included increased contaminant loading to assess material performance under more demanding conditions.

For expanded clay, three Leca products were evaluated, yielding reported removal ranges of 86–99% for Cu, 85–99% for Pb, 80–98% for Zn, and 76–> 90% for Phosphorus (P). For the base-case TEA, midpoint values of 92.5%, 92.0%, 89.0%, and 83.0%, respectively, were adopted. Values reported as > 90% were conservatively represented as 90% for numerical calculation. Filtralite P was used as the representative processed-clay medium, with reported removal efficiencies of 99% for Cu, > 99% for Pb, 99% for Zn, and > 90% for P; corresponding numerical model values of 99%, 99%, 99%, and 90% were therefore used. For biochar, the range between the tested birch- and spruce-derived biochars was used, resulting in base-case midpoint values of 89.0% for Cu, 88.0% for Pb, and 83.5% for Zn. Phosphorus performance varied substantially, including P release from one biochar, and was therefore treated as highly uncertain.

For the CDW-derived medium, direct long-term contaminant-removal data for the developed CDW–low-density polyethylene (LDPE) agglomerates are not yet available. The developed agglomerates have previously been evaluated for environmental leaching, chemical stability, and life-cycle cost (Munir et al., 2026b), but these tests did not provide long-term pollutant-removal efficiencies. Preliminary laboratory packed-bed experiments conducted within the StoPWa project using mixed CDW under synthetic-stormwater conditions were therefore used to inform plausible CDW performance scenarios. Based on these preliminary observations, Cu and Zn scenario ranges of 67–78% and 65–82%, respectively, were adopted for the comparative TEA. The midpoint of each range was used as the base-case model input, corresponding to 72.5% Cu removal and 73.5% Zn removal. These values should therefore be interpreted as scenario-based proxy inputs informed by preliminary column testing, rather than as experimentally validated long-term performance of the developed CDW agglomerates. No sufficiently robust Pb-removal value was available for the CDW agglomerate and Pb was therefore not assigned a quantitative CDW base-case value. Similarly, P behavior remained highly variable in the preliminary CDW datasets and leaching assessments; consequently, P-related CDW results were treated separately as uncertain scenario outcomes and were not interpreted as established removal performance. The sources, experimental configurations, reported ranges, and numerical inputs used in the TEA are summarized in Table S1.

Because the performance data originated from different experimental programmes, some uncertainty remains due to differences in influent composition, contaminant loading, contact time, particle size, and test configuration. Although the data were harmonized using representative values for the comparative TEA, these differences may introduce bias, and the removal efficiencies should therefore be interpreted as comparative model inputs rather than directly equivalent experimental measurements.

2.5. Economic inventory and cost assumptions

The economic analysis included material acquisition, processing, transport, installation, operation and maintenance expenditure (OPEX), media replacement, and end-of-life (EOL) management over the 50-year assessment period. Project-specific economic information for the CDW-derived system was obtained from the previously developed filtration system and its associated life-cycle cost assessment (Munir et al., 2026b), whereas benchmark economic information for conventional filtration media was compiled from technical reports, supplier information, and publicly available industrial sources.

To improve transparency and consistency in the comparative analysis, deterministic base-case values were distinguished from the broader parameter ranges used to characterize uncertainty. A single representative value was used for each parameter in the base-case NPC and LCOT calculations, whereas the broader ranges were considered as uncertainty bounds and, where applicable, evaluated through sensitivity analysis. The base-case economic inputs used in the model are summarized in Table 2.

For the CDW-derived medium, processing included pre-treatment of the CDW fraction, crushing and sieving, blending with the polymer binder, thermomechanical agglomeration, and subsequent grading of the produced agglomerates. The developed CDW material consisted of CDW blended with low-density polyethylene (LDPE) and processed using high-shear thermomechanical agglomeration at approximately 180–200 °C (Munir et al., 2026b). The broader processing-cost interval considered during model development reflects potential variability associated with processing scale, energy demand, labor requirements, and equipment use and was therefore treated as an uncertainty range rather than being directly used in the deterministic base-case calculation.

For the conventional filtration media, representative material and processing costs were harmonized to the same filtration-unit basis. Installation assumptions were kept identical across all evaluated systems to isolate the influence of media-dependent costs. Common operational assumptions were also applied where material-specific long-term economic data were unavailable. Uncertainty in the principal techno-economic parameters was subsequently evaluated through sensitivity analysis.

All base-case economic calculations were expressed on a consistent real-cost basis. No separate inflation escalation was applied

Table 1
Physical and conceptual characteristics of the evaluated filter media (indicative density ranges compiled from technical and industrial benchmark data).

Media	Primary source	Main processing route	Indicative bulk density (kg/m^3)	Particle size (mm)	Circularity potential
CDW-based agglomerates	CDW(concrete, brick, fines)	Collection → sorting → crushing → sieving → agglomeration (low temperature/mechanical)	1000–1600	0.2–10	High (waste valorization, reusable/recyclable)
Expanded clay	Natural clay	Clay extraction → pelletization → rotary kiln expansion (~1100–1200 °C)	250–800	2–10	Low–moderate (natural resource, energy-intensive, limited reuse)
Processed clay	Natural clay (engineered)	Clay extraction → crushing/sieving and thermal processing → grading	800–1400	1–10	Low–moderate (engineered mineral media with moderate reuse potential)
Biochar	Biomass (wood, agricultural residues)	Biomass collection → drying → pyrolysis (350–700 °C) → crushing/sieving	200–600	0.5–5	Moderate–high (renewable source, but variable sustainability)

Table 2
Economic input data used in the TEA.

Cost component	Unit	CDW	Expanded clay	Processed clay	Biochar
Material cost	€/filtration unit	100	900	1500	3000
Processing cost	€/filtration unit	900	1800	2200	2600
Transport cost	€/filtration unit	300	800	900	1400
OPEX contribution	€/filtration unit	2800	4200	5000	5800
Replacement cost	€/filtration unit	850	1400	1800	3000
EOL landfill cost	€/filtration unit	2500	800	1000	1200
EOL recycling credit	€/filtration unit	−1000	—	—	—
EOL reuse credit	€/filtration unit	−2000	—	—	—
Installation cost	€/filtration unit	3000	3000	3000	3000

Note: Values represent the deterministic base-case inputs used in the comparative NPC calculations. Broader parameter ranges were used to characterize uncertainty and were evaluated separately through sensitivity analysis. Negative end-of-life values represent recovered-value or avoided-disposal credits.

because all costs were expressed in constant real euros and discounted using a real discount rate. A real discount rate of 3.2% was adopted for present-value calculations. This value is consistent with the range commonly applied in European and Finnish public-infrastructure appraisal, including the approximately 3% benchmark recommended for Finland in European cost–benefit guidance and the 3.5% rate applied in Finnish transport-infrastructure appraisal. The 3.2% real discount rate was applied consistently across the base-case scenarios, while uncertainty analysis focused on parameters for which sufficiently supported variation ranges were available. A higher discount rate would reduce the present value of future OPEX and replacement costs, whereas a lower rate would increase their contribution to NPC; however, because the same discount rate was applied consistently across all alternatives, its primary effect is expected to be on absolute NPC rather than the overall comparative interpretation.

For transparency, the economic inputs were further classified according to their evidence basis as project-specific data, literature/market-derived data, or harmonized modelling assumptions. Project-specific CDW economic information was informed by the previously developed filtration system and associated life-cycle cost assessment (Munir et al., 2026b) and harmonized to the common filtration-unit basis used in the present comparison. Conventional-media inputs were derived from available technical documentation, published market information, and supplier information and were similarly harmonized to the common functional basis. Parameters for which directly comparable industrial data were unavailable, including common installation and some operational assumptions, were explicitly identified as modelling assumptions rather than site-specific or procurement-level cost data. Where sufficiently supported uncertainty ranges were available, their influence was evaluated through sensitivity analysis. The evidence basis, source category, and uncertainty treatment of the principal economic inputs are summarized in Table S2.

2.6. Techno-economic performance indicators

The techno-economic evaluation was performed using NPC, LCOT, and cost per unit pollutant removed. NPC was calculated as the sum of initial capital expenditure (CAPEX), discounted operation and maintenance expenditure (OPEX), discounted replacement costs, and end-of-life management costs over the assessment period. LCOT was determined by dividing NPC by the cumulative stormwater volume treated during the system lifetime, while the pollutant-removal cost was calculated by normalizing NPC against the cumulative pollutant mass removed. These indicators were selected to enable direct comparison between circular CDW-based media and conventional commercial filtration materials under harmonized system assumptions.

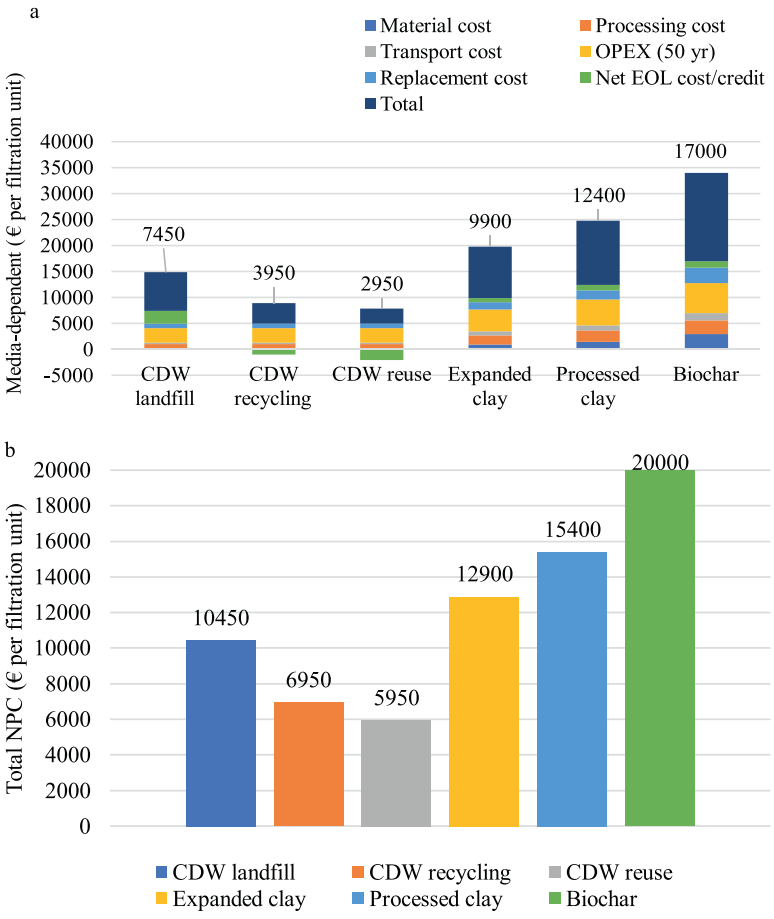
$$NPC = CAPEX + \sum_{t=1}^{T} \frac{OPEX_t}{(1+r)^t} + \sum_{j=1}^{n} \frac{RC_j}{(1+r)^{t_j}} + \frac{EOL}{(1+r)^T} \tag{1}$$

$$LCOT = \frac{NPC}{\sum_{t=1}^{T} Q_t} \tag{2}$$

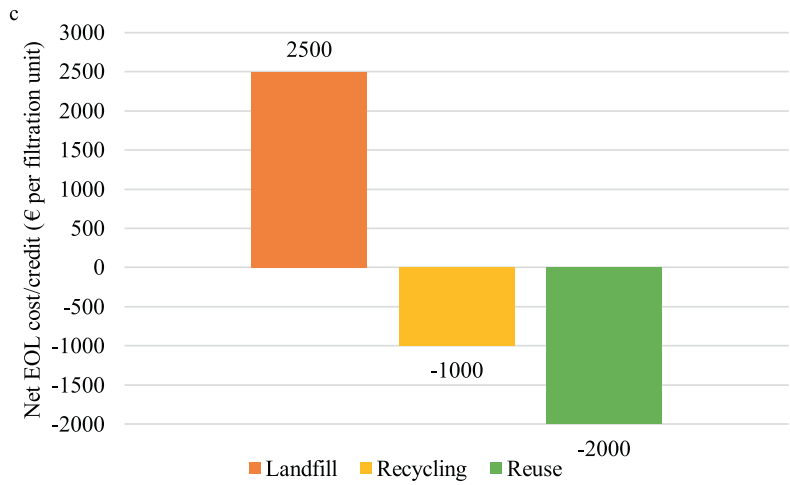
$$C_{pollutant} = \frac{NPC}{\sum_{t=1}^{T} M_{removed,t}} \tag{3}$$

where:

- T= analysis period
- r= discount rate
- RC_j= replacement cost at time t_j
- Q_t= treated stormwater volume
- $M_{removed,t}$= pollutant mass removed during year t;
- EOL = end-of-life management cost.



Note: Installation cost (€ 3,000/unit) is identical across all systems and included in total NPC.



Note: Negative values represent recovered values or avoided disposal cost.

Fig. 2. a presents the media-dependent life-cycle cost contributions under the base-case assumptions, excluding the common installation cost per filtration unit. The corresponding total NPC values, including installation, are presented in Fig. 2b, Net end-of-life cost/credit for CDW landfill, recycling, and reuse scenarios, are presented in Fig. 2c. Note: Installation cost (€ 3000/unit) is identical across all systems and included in total NPC. Note: Negative values represent recovered values or avoided disposal cost.

For the pollutant-specific cost-effectiveness comparison, Cu and Zn were selected because quantitative removal inputs were available for all evaluated media. A common high-loading synthetic-stormwater basis of 5 mg/L Cu and 20 mg/L Zn, corresponding to the StormFilter mixed-media test scenario, was applied uniformly across all alternatives. Cumulative pollutant mass removed was calculated from the common treated volume, influent concentration, and material-specific removal efficiency. Pb and P were excluded from the common cost-effectiveness calculation because quantitative CDW removal inputs were insufficiently robust.

2.7. Scenario assumptions and comparison framework

Four filtration-media alternatives were evaluated: CDW agglomerates, expanded clay, processed clay, and biochar. For the CDW-based system, multiple end-of-life pathways, including landfill disposal, recycling, and reuse, were assessed to capture different circularity scenarios. Conventional filtration media were evaluated using disposal-based end-of-life assumptions according to their expected service life. To ensure comparability, identical operational conditions, installation assumptions, and system boundaries were applied across all alternatives. The principal scenario assumptions and their corresponding evidence or modelling basis are summarized in Table S3.

The CDW recycling and reuse credits were treated as scenario-based avoided-disposal/recovery values rather than guaranteed market revenues. The assumed credits of €1000 and €2000 per 15-t unit correspond to approximately €67/t and €133/t, respectively. For context, Finnish waste-management tariffs show substantial differences between disposal and reusable CDW streams (HSY, 2026). Because actual recovery value depends on material quality and market conditions, a conservative zero-credit case was also evaluated.

The 50-year assessment period represents the overall structural and economic analysis horizon and does not imply a 50-year service life for the filtration media. Media replacement intervals were therefore treated separately as scenario-based assumptions. The StormFilter programme indicated that appropriately dimensioned filter media may maintain effective Cu, Pb, Zn, and P removal for approximately 5–10 + years in the absence of severe clogging (Holt et al., 2018). Because equivalent long-term field data are not yet available for all media evaluated here, the material-specific replacement intervals were treated as modelling assumptions rather than experimentally validated lifetimes, and their influence was explicitly examined over a broader 5–15-year range in the sensitivity analysis.

2.8. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the robustness of the TEA under changes in key operational and economic assumptions. The parameters examined were end-of-life/disposal cost, maintenance interval, transport distance, media replacement interval, and OPEX rate. These parameters were varied around the corresponding base-case assumptions to evaluate their influence on NPC and to determine whether the relative economic ranking of CDW-derived and conventional filtration media remained stable under plausible changes in long-term operating conditions.

To complement the one-factor sensitivity analysis and account for the simultaneous variation of uncertain techno-economic parameters, a probabilistic Monte Carlo analysis was performed. The same uncertainty ranges used in the deterministic sensitivity analysis were adopted for end-of-life/disposal cost, maintenance interval, transport distance, media replacement interval, and OPEX rate. Triangular probability distributions were assigned because minimum, base-case (most-likely), and maximum values were available, whereas sufficient empirical data were not available to justify more complex distribution forms. The ranges were 0.5–2.0 × for end-of-life/disposal cost, 3–6 years for maintenance interval, 0.5–2.0 × for transport distance, 5–15 years for media replacement interval, and 2–6% of CAPEX/year for OPEX. A total of 10,000 iterations were performed, with the uncertain parameters varied simultaneously in each iteration. The resulting NPC distributions were characterized using the median and the 5th–95th percentile interval. Pairwise probabilities were also calculated to evaluate the likelihood that the CDW-based scenarios retained lower NPC than the conventional benchmark alternatives. The real discount rate of 3.2% and the common installation cost were kept fixed because the probabilistic analysis was restricted to parameters for which supported uncertainty ranges had been established.

3. Results

3.1. Cost structure of evaluated filter media

The cost structure of the evaluated filtration media over the 50-year assessment period is presented in Fig. 2a–c. Clear differences were observed in the contributions of individual life-cycle cost components among the evaluated systems. Under the base-case assumptions, the CDW-based scenarios showed comparatively low material, processing, and transport-cost contributions because of the use of waste-derived feedstock, local sourcing assumptions, and lower-temperature processing. In contrast, expanded clay and processed clay showed higher production-related cost contributions associated with material preparation and thermal processing, while biochar exhibited the highest media-dependent cost because of higher material, processing, transport, and replacement-related contributions.

The choice of end-of-life (EOL) pathway substantially affected the media-dependent cost of the CDW system (Fig. 2a). The landfill scenario resulted in a positive EOL cost of €2500 per filtration unit, whereas recycling and reuse generated credits of €1000 and €2000 per unit, respectively. Consequently, the total media-dependent life-cycle cost decreased from €7450 for CDW landfill to €3950 for recycling and €2950 for reuse. These negative EOL contributions represent recovered material value and avoided disposal costs rather than negative physical expenditures.

Fig. 2b presents the corresponding total NPC values after inclusion of the common €3000 installation cost applied to all systems. Because installation was kept identical across the alternatives, differences in total NPC primarily reflect the media-dependent cost components shown in Fig. 2a. Fig. 2c further isolates the effect of the three CDW end-of-life pathways, illustrating the transition from a positive disposal burden under landfill to economic credits under recycling and reuse.

3.2. Net present cost comparison

The total NPC of the evaluated filtration-media scenarios is compared in Fig. 2b, while Figs. 3a and 3b present the corresponding absolute and relative cost savings achieved by the CDW-based scenarios against the conventional benchmark media. Under the base-case assumptions, total NPC was €10,450, €6950, and €5950 per filtration unit for the CDW landfill, recycling, and reuse scenarios, respectively, compared with €12,900 for expanded clay, €15,400 for processed clay, and €20,000 for biochar. All three CDW scenarios therefore exhibited lower modeled NPC than the conventional benchmark systems over the 50-year assessment period.

The magnitude of the economic difference depended on both the CDW end-of-life pathway and the benchmark material (Fig. 3a). Relative to expanded clay, the NPC savings were €2450 for CDW landfill, €5950 for recycling, and €6950 for reuse. The corresponding savings relative to processed clay were €4950, €8450, and €9450, while comparison with biochar yielded savings of €9550, €13,050, and €14,050, respectively. The larger savings associated with recycling and reuse reflect the avoided disposal burden and recovered-value credits assigned to these circular end-of-life pathways.

Expressed as relative reductions (Fig. 3b), the modeled NPC savings ranged from approximately 19–70% across the evaluated comparisons. For the landfill scenario, the reductions were approximately 19.0%, 32.1%, and 47.8% relative to expanded clay, processed clay, and biochar, respectively. Recycling increased these reductions to approximately 46.1%, 54.9%, and 65.3%, while the reuse scenario resulted in reductions of approximately 53.9%, 61.4%, and 70.3%, respectively. These results demonstrate that the modeled economic advantage of the CDW-derived system was influenced strongly by the selected end-of-life pathway, with circular recovery providing the largest reduction in lifetime cost.

3.3. Levelized cost of treatment

The LCOT values for all evaluated filtration-media scenarios are presented in Fig. 4. The corresponding LCOT values were €0.42/m^3 for CDW landfill, €0.28/m^3 for CDW recycling, and €0.24/m^3 for CDW reuse, compared with €0.52/m^3 for expanded clay, €0.62/m^3 for processed clay, and €0.80/m^3 for biochar. Consistent with the NPC analysis, CDW-derived systems exhibited the lowest treatment costs over the 50-year assessment period. Among the evaluated pathways, the CDW reuse scenario achieved the lowest LCOT value, followed

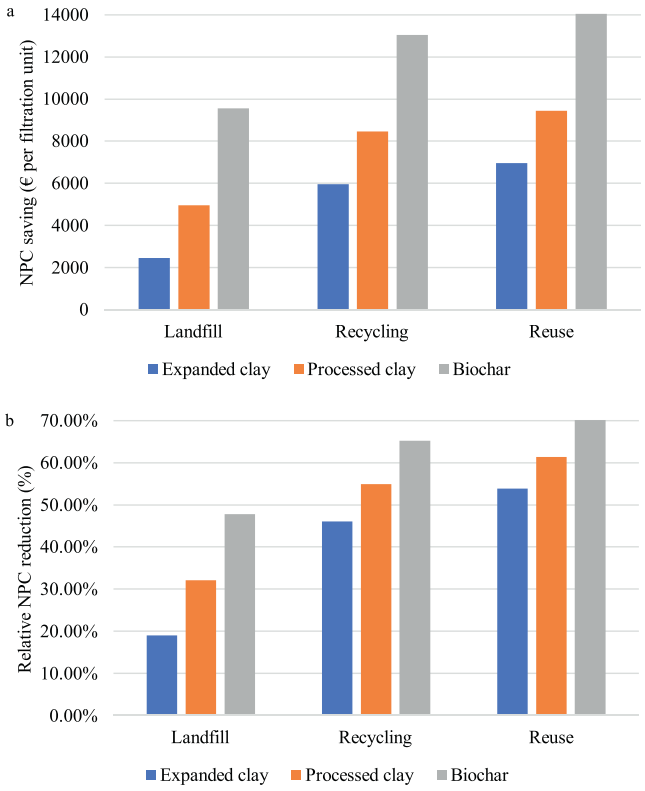


Fig. 3. (a). NPC savings of CDW scenarios relative to benchmark media (b) Relative NPC reduction of CDW-derived filtration media.

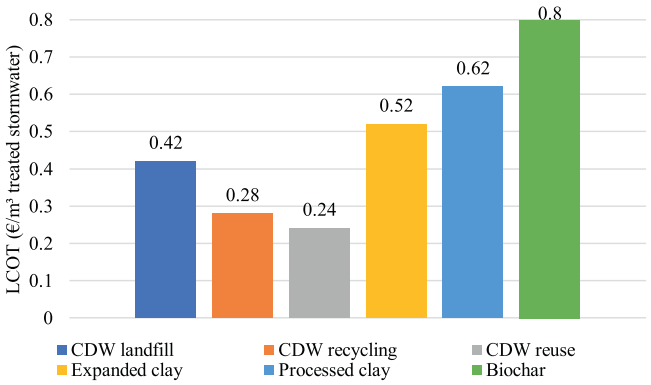


Fig. 4. LCOT comparison of evaluated filtration-media scenarios.

by recycling and landfill disposal scenarios. In contrast, expanded clay, processed clay, and biochar exhibited substantially higher LCOT values because of higher production intensity, replacement requirements, and transport-related costs.

The observed variation in LCOT primarily reflects differences in media-dependent costs because the same filtration-unit design basis, operational conditions, assessment period, and treated stormwater volume were applied across all scenarios (Fig. 4). Consequently, lower material and processing costs, combined with favorable end-of-life management, directly improved the treatment-cost efficiency of CDW-derived systems. In particular, recycling and reuse pathways reduced long-term treatment costs through avoided disposal burden and recovered-value credits associated with circular recovery strategies.

Among the conventional benchmark systems, biochar exhibited the highest LCOT because of comparatively high feedstock-processing costs and shorter replacement intervals, while processed clay also showed elevated treatment costs associated with thermal processing requirements. Expanded clay demonstrated intermediate economic performance but remained less cost-efficient than the evaluated CDW scenarios. Overall, the results demonstrate that CDW-derived filtration media can substantially reduce the long-term cost of decentralized stormwater treatment while maintaining strong techno-economic competitiveness under Nordic

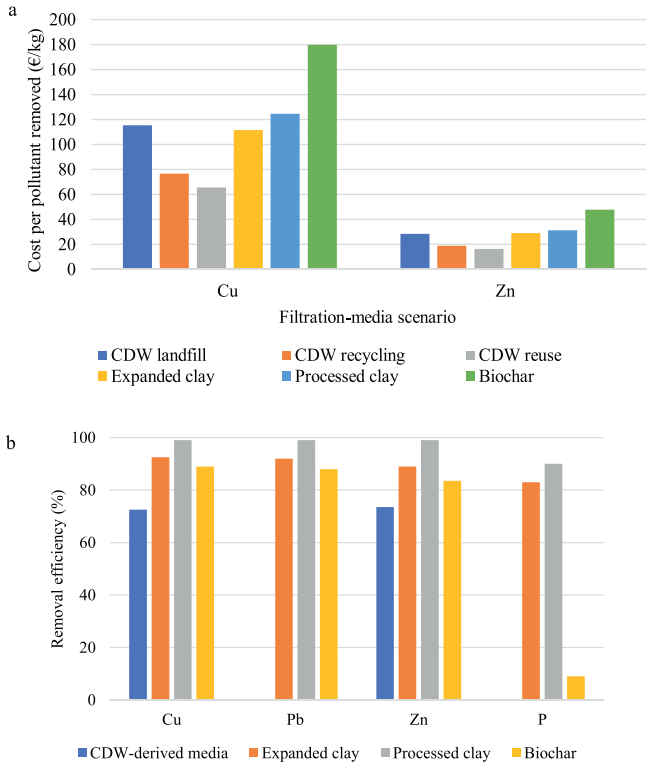


Fig. 5. (a) Pollutant-specific cost-effectiveness of the evaluated filtration-media scenarios for Cu and Zn, for which quantitative removal inputs were available across all media; (b) base-case contaminant-removal inputs used in the TEA for Cu, Pb, Zn, and P (Quantitative CDW Pb and P values were not assigned because sufficiently robust performance data were unavailable).

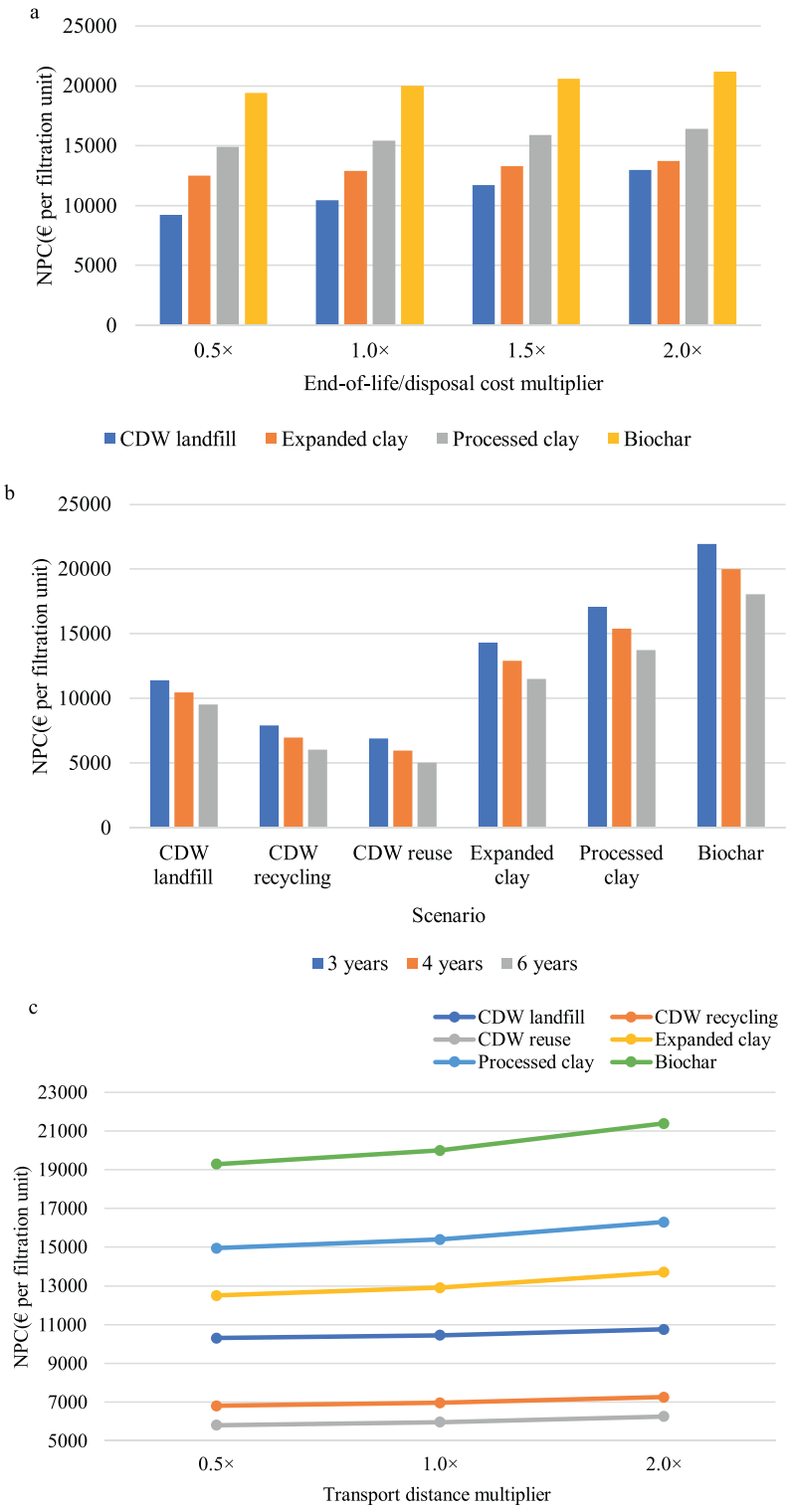


Fig. 6. Sensitivity analysis of the evaluated filtration-media scenarios under varying techno-economic assumptions: (a) influence of end-of-life/disposal cost escalation, (b) effect of maintenance interval variation, (c) sensitivity to transport distance, (d) influence of media replacement interval, and (e) effect of OPEX rate variation on NPC.

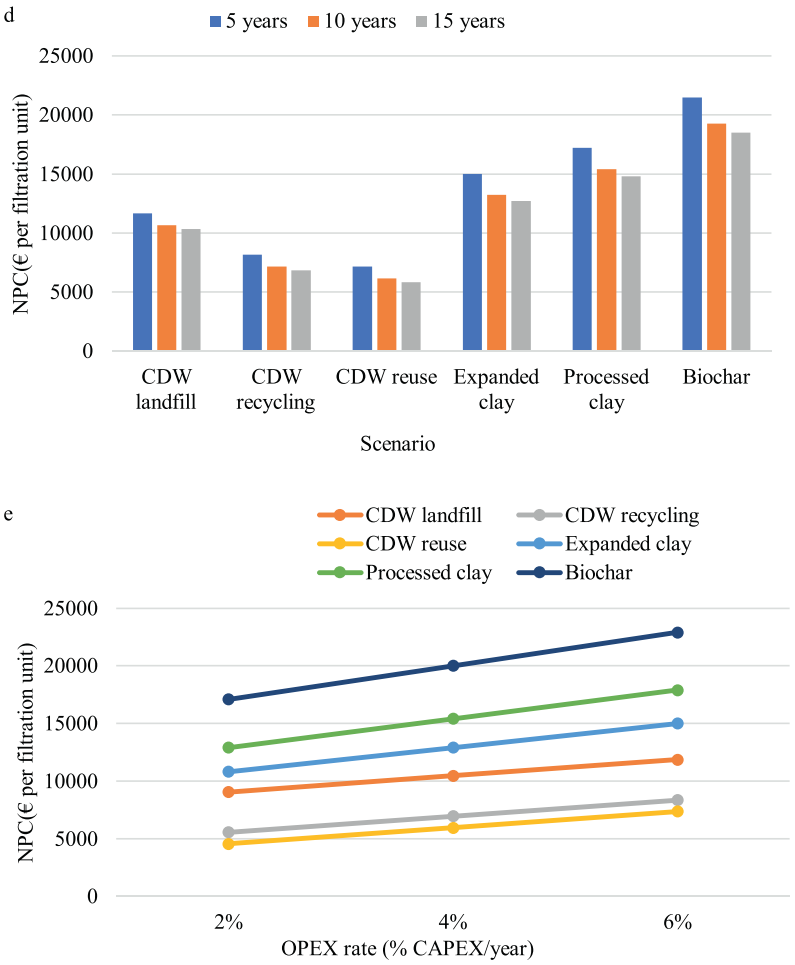


Fig. 6. (*continued*).

operating conditions.

3.4. Cost-effectiveness in terms of contaminant removal

The pollutant-specific cost-effectiveness of the evaluated filtration-media scenarios is presented in Fig. 5a for Cu and Zn, the two contaminants for which quantitative removal inputs were available across all evaluated media. Under the common high-loading influent assumptions, the modeled Cu-removal costs were €115.31/kg for CDW landfill, €76.69/kg for CDW recycling, and €65.66/kg for CDW reuse, compared with €111.57/kg for expanded clay, €124.44/kg for processed clay, and €179.78/kg for biochar. For Zn, the corresponding costs were €28.44/kg, €18.91/kg, and €16.19/kg for the three CDW scenarios, compared with €28.99/kg for expanded clay, €31.11/kg for processed clay, and €47.90/kg for biochar. The CDW recycling and reuse scenarios therefore exhibited the lowest modeled cost per unit of Cu and Zn removed, whereas biochar showed the highest pollutant-specific cost under the adopted assumptions.

The contaminant-removal inputs used in the TEA are compared in Fig. 5b. For the CDW-derived medium, the quantitative base-case inputs were 72.5% for Cu and 73.5% for Zn; no fixed quantitative values were assigned for Pb or P because sufficiently robust data were unavailable. Expanded clay used base-case removal values of 92.5% for Cu, 92.0% for Pb, 89.0% for Zn, and 83.0% for P. The corresponding processed-clay values were 99%, 99%, 99%, and 90%, respectively, while biochar values were 89.0% for Cu, 88.0% for Pb, 83.5% for Zn, and 9.0% for P. The biochar P value represents a scenario-based midpoint of a highly variable reported range and should therefore not be interpreted as stable long-term phosphorus-removal performance.

Despite the lower Cu and Zn removal efficiencies adopted for the CDW scenario, the recycling and reuse pathways achieved favorable pollutant-specific cost-effectiveness because of their lower NPC and circular end-of-life credits. The results therefore show that removal efficiency alone does not determine economic performance; life-cycle cost and end-of-life management also strongly influence the cost per unit of pollutant removed. Pb and P were retained in Fig. 5b to illustrate the broader technical-performance characteristics of the filtration media but were excluded from the common pollutant-specific cost comparison because equivalent

quantitative CDW inputs were unavailable.

3.5. Performance–cost trade-off

The evaluated filtration media exhibited distinct trade-offs between contaminant-removal performance and long-term economic competitiveness. Processed clay demonstrated the highest overall removal efficiency, particularly for Cu, Zn, and Pb, but also exhibited comparatively high treatment cost because of energy-intensive production processes and higher replacement-related burden. Similarly, biochar showed relatively strong contaminant-removal performance; however, its economic competitiveness was reduced by comparatively high material-processing and operational costs.

Expanded clay represented an intermediate case, providing relatively high contaminant-removal efficiency while maintaining moderate treatment cost and operational requirements. In contrast, the CDW-derived filtration media demonstrated moderate but promising contaminant-removal performance combined with substantially lower life-cycle treatment cost and high circularity potential. Although the contaminant-removal efficiencies of CDW-derived systems remained lower than those of conventional benchmark materials, their lower economic burden and waste-valorization potential improved their overall techno-economic attractiveness.

The results indicate that filtration-media selection should depend on application priorities, treatment targets, and economic constraints. Conventional filtration materials may be preferable where maximum contaminant-removal efficiency is the primary design objective, whereas CDW-derived systems may provide a more favorable balance between treatment performance, circularity, and economic feasibility for decentralized and cost-sensitive stormwater treatment applications. Overall, the findings highlight the importance of integrating both technical and economic indicators when evaluating circular stormwater filtration materials.

3.6. Sensitivity to key assumptions

The sensitivity analysis was performed to evaluate the robustness of the TEA under varying operational and economic assumptions. The analysis considered the influence of end-of-life/disposal cost, maintenance interval, transport distance, media replacement interval, and OPEX rate on the NPC of the evaluated filtration-media scenarios (Fig. 6).

An increase in end-of-life and disposal costs resulted in a noticeable rise in NPC for disposal-based scenarios, particularly for the CDW landfill route and conventional benchmark materials relying on final disposal pathways (Fig. 6a). This trend highlights the growing economic burden associated with landfill-dependent waste management strategies under stricter environmental and disposal regulations. In contrast, CDW recycling and reuse scenarios remained comparatively stable because the circular recovery pathways reduced disposal dependency and enabled recovered-value credits, thereby mitigating the influence of disposal-cost escalation (Fig. 6a).

The maintenance interval significantly affected long-term economic performance (Fig. 6b). Reducing the maintenance interval from six to three years increased NPC by approximately 15–32% depending on the evaluated filtration media. The effect was most pronounced for biochar and processed clay because of their comparatively higher operational requirements, while CDW-derived systems showed lower sensitivity due to their lower baseline maintenance burden. Conversely, extending the maintenance interval reduced lifetime costs and improved overall economic competitiveness by decreasing the cumulative operational burden over the 50-

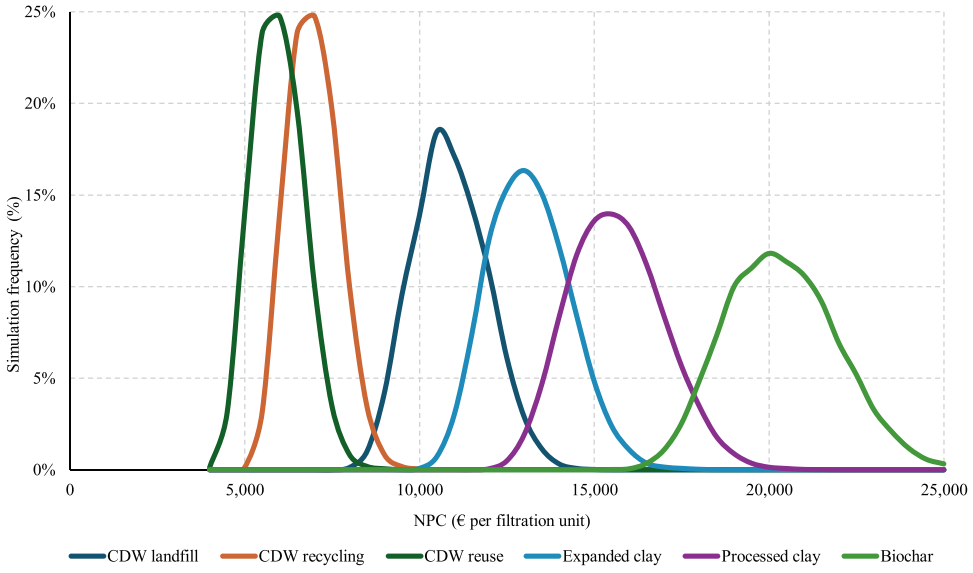


Fig. 7. Monte Carlo distributions of NPC for the evaluated filtration-media scenarios based on 10,000 iterations with simultaneous variation of key techno-economic parameters.

year assessment period (Fig. 6b).

Transport-distance variation also influenced the techno-economic outcome, although to a lesser extent than maintenance and replacement assumptions (Fig. 6c). Increasing the transport-distance multiplier from 0.5 × to 2.0 × increased the NPC of the CDW landfill scenario from approximately €10,300 to €10,750, whereas biochar increased from approximately €19,300 to €21,400. This corresponds to the approximately 4–11% variation observed across the evaluated systems.

The influence of media replacement interval is presented in Fig. 6d. Shortening the media replacement interval from 15 to 5 years increased the NPC of the CDW reuse scenario from approximately €5850 to €7150 and that of biochar from approximately €18,500 to €21,500 per filtration unit. In contrast, CDW-derived systems exhibited comparatively lower variation, indicating greater economic stability under changing replacement assumptions. These findings demonstrate that replacement frequency is a critical parameter governing the long-term economic competitiveness of filtration materials (Fig. 6d). The variation in OPEX rate further confirmed the importance of operational assumptions in long-term cost assessment (Fig. 6e). Increasing the OPEX rate from 2% to 6% increased the NPC of the CDW reuse scenario from approximately €4550 to €7350 per filtration unit, while the corresponding NPC of biochar increased from approximately €17,100 to €22,900. The CDW landfill scenario increased from approximately €9050 to €11,850 over the same OPEX range. Despite these variations, CDW recycling and reuse maintained lower NPC values than the conventional benchmark systems.

In the zero-credit case, removing the €1000 recycling and €2000 reuse credits increased the NPC of both CDW scenarios to €7950 per filtration unit. This remained approximately 38.4%, 48.4%, and 60.3% below expanded clay, processed clay, and biochar, respectively, indicating that the modeled CDW cost advantage was not solely dependent on the assumed EOL credits.

3.7. Probabilistic uncertainty analysis

The Monte Carlo analysis further evaluated the robustness of the economic comparison under simultaneous variation of the principal uncertain parameters (Fig. 7). The median NPC values were approximately €10,831 for CDW landfill, €6927 for CDW recycling, and €5927 for CDW reuse, compared with €13,077 for expanded clay, €15,579 for processed clay, and €20,289 for biochar. The corresponding 5th–95th percentile ranges were €9225–12,693, €5848–8208, and €4848–7208 for the three CDW scenarios, respectively, compared with €11,350–15,133 for expanded clay, €13,558–17,958 for processed clay, and €17,875–23,135 for biochar.

Despite simultaneous variation in end-of-life cost, maintenance interval, transport distance, replacement interval, and OPEX, the CDW recycling and reuse scenarios retained lower NPC than all three conventional benchmark media in 100% of the simulations. The CDW landfill scenario also remained less costly than processed clay and biochar in 100% of simulations and less costly than expanded clay in approximately 99.99% of simulations. These results indicate that the relative economic advantage of the CDW scenarios, particularly recycling and reuse, remained robust under the combined uncertainty ranges considered in the analysis.

4. Discussion

4.1. Techno-economic positioning of CDW-derived filter media

The present study shows that CDW-derived filtration media occupy a distinct techno-economic position among the evaluated decentralized stormwater-treatment materials. Under the harmonized base-case assumptions, the CDW scenarios exhibited lower NPC and LCOT than expanded clay, processed clay, and biochar, while their modeled Cu and Zn removal efficiencies remained lower than those of the conventional benchmark media. The economic advantage of the CDW-derived system was primarily associated with the low cost of waste-derived feedstock, comparatively low-temperature processing, local sourcing assumptions, and favorable end-of-life pathways.

This interpretation is consistent with the project-specific life-cycle cost assessment previously reported for CDW-derived stormwater filtration, in which processing route and end-of-life management strongly influenced overall economic performance (Munir et al., 2026b). More broadly, reviews of CDW management and circular construction identify waste valorization, secondary-resource substitution, and industrial symbiosis as important pathways for reducing reliance on virgin resources (Cudecka-Purina et al., 2024; da Silva et al., 2026). These broader studies provide context for the circular-resource rationale of the present work but are not direct techno-economic comparisons of stormwater filtration media.

In contrast, the conventional clay-based media evaluated in the present study are associated with energy-intensive thermal-processing routes, including kiln temperatures approaching 1100–1200 °C. Such processing requirements have been reported as important contributors to the embodied energy and production burden of lightweight and processed clay materials (Torabi-Kaveh et al., 2021; Pishdadi-Aghdarreh et al., 2023; Uslu et al., 2024). Biochar showed strong modeled contaminant-removal performance but comparatively high lifetime cost, consistent with literature showing that biochar economics can be strongly influenced by feedstock characteristics, pyrolysis conditions, production scale, and replacement requirements (Campion et al., 2023; Ahmed et al., 2024).

4.2. Influence of circular end-of-life pathways

End-of-life management was one of the main factors differentiating the CDW scenarios. Recycling and reuse reduced NPC and LCOT relative to landfill disposal because the model assigned avoided-disposal costs and recovered-value credits to these pathways. The result therefore demonstrates that the economic performance of waste-derived filter media depends not only on initial material cost but also on the value and cost structure associated with their management after use.

This finding is directly consistent with the earlier life-cycle cost assessment of the developed CDW filtration system, which also demonstrated sensitivity to alternative end-of-life pathways (Munir et al., 2026b). Broader CDW-management literature similarly emphasizes recycling, secondary-resource recovery, and circular material use as key strategies for improving the value retained from construction waste (Soto-Paz et al., 2023; da Silva et al., 2026). These studies are used here to contextualize the circular-management principle rather than as quantitative evidence for the specific NPC reductions calculated in the present study. Also, recent life-cycle assessment (LCA) studies further support the importance of circular waste-management pathways. Kanwal et al. (2025) demonstrated environmental benefits of CDW recycling relative to disposal, while Kanwal et al. (2026) highlighted the value of integrating circular-economy strategies with LCA-based indicators in industrial waste management. Although these studies address different geographical and system contexts, they reinforce the importance of complementing economic assessment with environmental indicators when evaluating circular CDW pathways.

The relevance of such recovery pathways is particularly clear in the European context, where high reported CDW recovery rates do not necessarily imply high-value circular use. Reviews of European CDW management have identified substantial differences in recovery practices among countries, while recent assessments indicate that a large proportion of treated CDW remains directed toward low-value recovery or downcycling routes (Moschen-Schimek et al., 2023; Zhang et al., 2026a). The present results therefore illustrate how higher-value reuse or recycling of CDW-derived filtration media could improve resource retention while also reducing modeled end-of-life cost.

4.3. Performance–cost trade-offs and key economic drivers

The results demonstrate a clear trade-off between contaminant-removal performance and life-cycle cost. Processed clay provided the highest modeled removal efficiencies for Cu, Zn, and Pb but also showed comparatively high NPC and LCOT. Expanded clay represented an intermediate case, combining relatively high removal performance with moderate economic burden. By comparison, the CDW-derived media showed lower Cu and Zn removal inputs but substantially lower lifetime cost, particularly under recycling and reuse scenarios. These findings indicate that filtration-media selection should be based on treatment objectives, pollutant targets, and economic constraints rather than removal efficiency alone.

Previous stormwater studies have similarly shown that life-cycle economic performance depends strongly on system configuration, design, and long-term operational assumptions. For example, Abdeljaber et al. (2022) evaluated cost-integrated life-cycle performance of low-impact development controls, while Garbanzos and Maniquiz-Redillas (2022) examined cost-effectiveness within a decentralized low-impact development design framework. These studies operate at the stormwater-system rather than filter-media level and are therefore used here as supporting evidence for the importance of integrating technical performance and life-cycle cost, rather than as directly comparable media-level benchmarks. The present study extends this perspective by applying the same principle specifically to filtration-media selection.

The sensitivity analysis further showed that OPEX, maintenance interval, replacement frequency, transport distance, and end-of-life cost can materially influence NPC. Shorter replacement intervals and higher OPEX produced the largest increases in modeled lifetime cost, while transport variation had a smaller effect. These results reinforce the need to interpret the base-case ranking together with uncertainty in long-term operating conditions. For CDW-derived media specifically, future optimization should therefore address not only contaminant removal but also durability, clogging resistance, replacement frequency, and maintenance requirements.

The probabilistic uncertainty analysis further supported the robustness of the comparative economic results. Despite simultaneous variation in the principal uncertain techno-economic parameters, the CDW recycling and reuse scenarios retained lower NPC than the conventional benchmark alternatives across all Monte Carlo simulations, while the CDW landfill scenario also remained less costly in virtually all simulated cases. This indicates that the modeled economic advantage of the circular CDW pathways was not dependent on a single deterministic combination of input assumptions.

4.4. Nordic applicability, limitations, and future research

The Nordic context introduces additional considerations for the practical application of CDW-derived filtration media. Cold-climate stormwater infrastructure is affected by seasonal conditions, including snowmelt, freeze–thaw processes, and variable hydraulic loading, which may influence filtration performance and maintenance requirements. Climate-change adaptation literature for urban water infrastructure further emphasizes the need for systems that remain robust under changing hydraulic and climatic conditions (Ferdowsi et al., 2024). Under such conditions, locally available secondary materials could offer logistical and economic advantages; however, these potential benefits require field validation.

Where very high or stable pollutant removal is required, particularly for phosphorus, engineered media such as processed clay may remain better suited because the benchmark data used in this study indicate higher and more consistent removal performance. Conversely, CDW-derived media may be relevant where circular material use and economic constraints are important design considerations. These conclusions should nevertheless be interpreted in light of the scenario-based nature of the CDW performance inputs.

Several limitations remain. Hydraulic parameters such as permeability, hydraulic conductivity, pressure drop/head loss, and clogging progression were outside the scope of the present TEA and were therefore not explicitly modeled. Long-term field-scale contaminant-removal data for the developed CDW agglomerates are not yet available, and the present assessment therefore relies partly on preliminary project data and scenario-based assumptions. In addition, several economic parameters required harmonized modelling assumptions because directly comparable industrial or procurement-level data were unavailable across all evaluated filtration media. Accordingly, the absolute NPC and LCOT values should be interpreted as comparative scenario-based estimates rather

than procurement-level cost forecasts. The analysis also does not include a full environmental LCA within the same framework. Future work should validate hydraulic performance, contaminant breakthrough, clogging behavior, regeneration potential, freeze–thaw durability, and replacement frequency under realistic operating conditions. Further validation using project-specific industrial quotations and operational cost data would also strengthen the economic assessment. Integrating TEA with environmental LCA would further enable economic and environmental trade-offs to be evaluated within a common decision-support framework.

At a broader level, the use of CDW-derived filtration media illustrates a potential pathway for linking urban waste recovery with decentralized stormwater management. Rather than treating this as an independent sustainability claim, the present results suggest that such integration may provide value when circular-material objectives coincide with acceptable treatment performance and favorable life-cycle economics. Application of the framework to other regions would require recalibration of the principal climatic, logistical, economic, and waste-management inputs using region-specific data.

5. Conclusions

This study presented a scenario-based TEA of CDW-derived filtration media for decentralized stormwater treatment and compared their modeled performance with expanded clay, processed clay, and biochar under harmonized system assumptions. Under the adopted base-case assumptions, the CDW-derived scenarios resulted in lower modeled NPC and LCOT than the selected conventional benchmarks, primarily because of lower assumed feedstock and processing costs and the potential economic benefits associated with circular end-of-life pathways. These findings should be interpreted as comparative techno-economic estimates rather than demonstrated field-scale economic superiority, because long-term contaminant-removal performance, hydraulic behavior, and replacement requirements of the developed CDW agglomerates have not yet been validated under extended field conditions.

Among the modeled scenarios, CDW recycling and reuse produced the lowest NPC and LCOT values. Although processed clay demonstrated higher contaminant-removal efficiencies, the scenario analysis indicates that CDW-derived media may provide a favorable performance–cost balance where suitable waste streams and circular recovery pathways are available. The sensitivity and probabilistic uncertainty analyses further indicate that the modeled economic comparison remains robust within the uncertainty ranges considered; however, long-term field validation remains necessary before the results can be translated into site-specific investment or procurement decisions.

Overall, the results indicate the potential of CDW-derived filtration media as a low-cost and circular alternative for decentralized stormwater treatment, subject to validation of long-term treatment, hydraulic, and durability performance under realistic operating conditions. Future work should focus on long-term pilot-scale validation, hydraulic and clogging behavior, freeze–thaw durability, and integrated environmental life-cycle assessment to further strengthen the applicability of CDW-based stormwater filtration systems.

CRediT authorship contribution statement

Qaisar Munir: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Timo Kärki:** Supervision, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2026.105256.

Data availability

The data used for the research described in the article

References

Abdeljaber, A., Adghim, M., Abdallah, M., Ghanima, R., ALjassem, F., 2022. Comparative performance and cost-integrated life cycle assessment of low impact development controls for sustainable stormwater management. Environ. Impact Assess. Rev. 95, 106805.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33.
Ahmed, S.F., Mehejabin, F., Chowdhury, A.A., Almomani, F., Khan, N.A., Badruddin, I.A., Kamangar, S., 2024. Biochar produced from waste-based feedstocks: Mechanisms, affecting factors, economy, utilization, challenges, and prospects. GCB Bioenergy. 16 (8), e13175.
Barbosa, A.E., Fernandes, J.N., David, L.M., 2012. Key issues for sustainable urban stormwater management. Water Res. 46 (20), 6787–6798.
Bolourieh, N., Kinnarinen, T., Virolainen, S., 2026. Utilizing construction and demolition waste particles as porous media for water filtration: Experimental characterization and ANN-based predictive modeling. Sep. Purif. Technol., 137268
Campion, L., Bekchanova, M., Malina, R., Kuppens, T., 2023. The costs and benefits of biochar production and use: A systematic review. J. Clean. Prod. 408, 137138.
City of Helsinki, 2025. Hulevesien hallinta tonteilla. Rakennusvalvonnan ohje, October 2025. City of Helsinki, Finland.
Conley, G., Beck, N., Riihimaki, C.A., Tanner, M., 2020. Quantifying clogging patterns of infiltration systems to improve urban stormwater pollution reduction estimates. Water Res. X 7, 100049.
Cudecka-Purina, N., Kuzmina, J., Butkevics, J., Olena, A., Ivanov, O., Atstaja, D., 2024. A comprehensive review on construction and demolition waste management practices and assessment of this waste flow for future valorization via energy recovery and industrial symbiosis. Energies 17 (21), 5506.
da Silva, S.R., Borges, P.M., Tošić, N., Andrade, J.J.D.O., 2026. Advances in circular valorization of construction and demolition waste (CDW) toward low-carbon and resilient construction: A Comprehensive review. Sustainability 18 (6), 2759.
Deng, X., Cao, Z., He, W., Vidal, G.V., Jiang, C., Xiao, F., 2026. Hierarchical applications of brick-concrete construction and demolition waste: From concrete/mortar to pavement engineering and pollutant adsorption. J. Traffic Transp. Eng. (Engl. Ed.).
Ferdowsi, A., Piadeh, F., Behzadian, K., Mousavi, S.F., Ehteram, M., 2024. Urban water infrastructure: A critical review on climate change impacts and adaptation strategies. Urban. Clim. 58, 102132.
Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.L., Mikkelsen, P.S., 2015. SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. Urban. Water J. 12 (7), 525–542.
Ganzi, G., Pronti, A., 2026. Cost–Benefit Analysis of Biochar Production: The Case Study of an Abandoned Rural Site, Borgo di Perolla, in Tuscany, Italy. Biomass 6 (2), 19.
Garbanzos, S., Maniquiz-Redillas, M., 2022. Modeling the hydrologic performance and cost-effectiveness of LID in a residential park area using a decentralized design approach. Hydrology 9 (4), 62.
Garfansa, M.P., Zalizar, L., Husen, S., Triwanto, J., Iswahyudi, I., Bakhtiar, A., Lasaksi, P., Ekalaturrahmah, Y.A.C., 2025. Addition of biochar based-activated carbon into sand filtration columns to improved removal efficiency microplastic from water. Bioresour. Technol. Rep. 30, 102099.
Göbel, P., Dierkes, C., Coldewey, W.G., 2007. Storm water runoff concentration matrix for urban areas. J. Contam. Hydrol. 91 (1-2), 26–42.
He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., Bryan, B.A., 2021. Future global urban water scarcity and potential solutions. Nat. Commun. 12 (1), 4667.
Helsinki Region Environmental Services Authority (HSY), 2026. Waste management service fees 2026. Helsinki Region Environmental Services Authority, Finland.
Holt, E., Korkealaakso, J., Wendling, L., Koivusalo, H., Sillanpää, N., 2018. Filtration Systems for Stormwater Quantity and Quality Management: Guideline for Finnish Implementation. VTT Technology 338. VTT Technical Research Centre of Finland Ltd, Espoo, Finland. ISBN 978-951-38-8666-0.
Hossain, I., Imteaz, M.A., Hossain, M.I., 2012. Application of a catchment water quality model for an East-Australian catchment. Int. J. Glob. Environ. Issues 12 (2-4), 242–255.
Jokinen, P., Pirinen, P., Kaukoranta, J.-P., Kangas, A., Alenius, P., Eriksson, P., Johansson, M., Wilkman, S., 2021. Climatological and Oceanographic Statistics of Finland 1991–2020. Reports 2021:8. Finnish Meteorological Institute, Helsinki. https://doi.org/10.35614/isbn.9789523361485.
Kalhori, E.M., Yetilmezsoy, K., Uygur, N., Zarrabi, M., Shmeis, R.M.A., 2013. Modeling of adsorption of toxic chromium on natural and surface modified lightweight expanded clay aggregate (LECA). Appl. Surf. Sci. 287, 428–442.
Kanwal, Q., Xu, G., Al-Ghamdi, S.G., 2026. Toward a circular Kuznets curve: integrating circular economy and life cycle assessment into industrial waste modeling. Front. Sustain. 7, 1684411. https://doi.org/10.3389/frsus.2026.1684411.
Kanwal, Q., Xu, G., Gari, Z., Alhusainan, R.S., Al-Ghamdi, S.G., 2025. Attributional life cycle assessment of recycling and disposal strategies for construction and demolition waste. Clean. Environ. Syst. 18, 100283. https://doi.org/10.1016/j.cesys.2025.100283.
Kumar, S., Ghosh, N.C., Kazmi, A.A., Jain, S.K., Kumar, V., Rajpal, A., 2020. Hybrid approach for urban hilly catchment runoff modelling and prediction of pollutant loads. Hydrol. Sci. J. 65 (15), 2535–2547.
Kumar, S., Vishwakarma, R.K., Tyagi, V.K., Kumar, V., Kazmi, A.A., Ghosh, N.C., Sasidharan, S., Nayak, P.C., Maurya, N.S., Hasan, R., Joshi, H., 2024. Stormwater runoff characterization and adaptation of best management practices under urbanization and climate change scenarios. J. Hydrol. 635, 131231.
Lancaster, E., Winston, R., Martin, J., Lee, J., 2024. Urban stormwater green infrastructure: Evaluating the public health service role of bioretention using microbial source tracking and bacterial community analyses. Water Res. 259, 121818.
Li, C., Liu, M., Hu, Y., Zong, M., Zhao, M., Todd Walter, M., 2019. Characteristics of impervious surface and its effect on direct runoff: a case study in a rapidly urbanized area. Water Supply 19 (7), 1885–1891.
Liu, M., Wang, Z., Wang, M., Li, X., Zhang, Y., Yang, B., Lai, C., 2025. A framework for optimization and assessment of long-term urban stormwater management scenarios under climate change and performance challenges. J. Environ. Manag. 390, 126298.
Liu, Y., Cibin, R., Bralts, V.F., Chaubey, I., Bowling, L.C., Engel, B.A., 2016. Optimal selection and placement of BMPs and LID practices with a rainfall-runoff model. Environ. Model. & Softw. 80, 281–296.
Lucas, R., Earl, E.R., Babatunde, A.O., Bockelmann-Evans, B.N., 2015. Constructed wetlands for stormwater management in the UK: a concise review. Civil. Eng. Environ. Syst. 32 (3), 251–268.
McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol. Sci. J. 61 (13), 2295–2311.
Mederos, M., Pla, C., Valdes-Abellan, J., Benavente, D., 2024. Evaluating nickel removal efficacy of Filtralite under laboratory conditions: Implications for sustainable urban drainage systems. J. Water Process. Eng. 63, 105416.
Mlih, R., Bydalek, F., Klumpp, E., Yaghi, N., Bol, R., Wenk, J., 2020. Light-expanded clay aggregate (LECA) as a substrate in constructed wetlands–A review. Ecol. Eng. 148, 105783.
Mohan, D., Sarswat, A., Ok, Y.S., Pittman Jr, C.U., 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresour. Technol. 160, 191–202.
Moschen-Schimek, J., Kasper, T., Huber-Humer, M., 2023. Critical review of the recovery rates of construction and demolition waste in the European Union–An analysis of influencing factors in selected EU countries. Waste Manag. 167, 150–164.
Müller, A., Österlund, H., Marsalek, J., Viklander, M., 2020. The pollution conveyed by urban runoff: A review of sources. Sci. Total. Environ. 709, 136125.
Munir, Q., Lahtela, V., Kärki, T., Khan, M.M.H., 2026b. Recycling of construction and demolition waste fines for decentralized stormwater filtration: Environmental leaching and life-cycle cost assessment. Waste Manag. Bull., 100307
Munir, Q., Lahtela, V., Kärki, T., Koivula, A., 2024. Assessing life cycle sustainability: A comprehensive review of concrete produced from construction waste fine fractions. J. Environ. Manag. 366, 121734.
Munir, Q., Lahtela, V., Rasilainen, I., Kärki, T., Khan, M.M.H., 2026a. Optimizing landfilled construction and demolition waste fractions for concrete: Recycling, design, and cost analysis. Sustain. Horiz. 18, 100189.
Ok, Y.S., Palansooriya, K.N., Yuan, X., Rinklebe, J., 2022. Special issue on biochar technologies, production, and environmental applications in Critical Reviews in Environmental Science & Technology during 2017–2021. Crit. Rev. Environ. Sci. Technol. 52 (19), 3375–3383.
Omar, A.N., McCaughan, K.J., Sharma, M., Kniel, K.E., 2026. Evaluation of Novel Filtration System Utilizing Biochar, Zero-Valent Iron and White Rot Fungi to Inhibit Foodborne Pathogenic Bacteria, Viruses and Protozoan Parasites. J. Food Prot., 100746
Patterson, C.L., Haught, R.C., 2021. Regulatory considerations to ensure clean and safe drinking water. Handbook of water purity and quality. Academic Press, pp. 93–135.

Paule-Mercado, M.A., Ventura, J.S., Memon, S.A., Jahng, D., Kang, J.H., Lee, C.H., 2016. Monitoring and predicting the fecal indicator bacteria concentrations from agricultural, mixed land use and urban stormwater runoff. Sci. Total. Environ. 550, 1171–1181.
Pishdadi-Aghdarreh, F., Norouzbeigi, R., Velayi, E., 2023. Acid-base treatment of lightweight expanded clay aggregate (LECA) for removal of paraquat from aqueous media. J. Environ. Chem. Eng. 11 (5), 110405.
Pitropova, I.S., Andersen, T.R., Søborg, D.A., Storm, S., Aggerlund, K., Raabjerg, T.E., Vollertsen, J., 2026. From waste to resource. Stormwater treatment using crushed concrete and iron-coated granulate in pilot-scale bioretention cells. J. Water Process. Eng. 87, 110056.
Rodak, C.M., Moore, T.L., David, R., Jayakaran, A.D., Vogel, J.R., 2019. Urban stormwater characterization, control, and treatment. Water Environ. Res. 91 (10), 1034–1060.
Soltaninia, S., Taghavi, L., Hosseini, S.A., Motamedvaziri, B., Eslamian, S., 2022. The effect of land-use type and climatic conditions on heavy metal pollutants in urban runoff in a semi-arid region. Water Reuse 12 (4), 384–402.
Soto-Paz, J., Arroyo, O., Torres-Guevara, L.E., Parra-Orobio, B.A., Casallas-Ojeda, M., 2023. The circular economy in the construction and demolition waste management: A comparative analysis in emerging and developed countries. J. Build. Eng. 78, 107724.
Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Sci. Rep. 10 (1), 13768.
Tang, R., Qiu, S., Wu, C., Tan, J., 2025. Biochar: from agricultural waste byproducts to novel adsorbents for ammonia and micro/nanoplastics (MNPs). Biochar 7 (1), 122.
Torabi-Kaveh, M., Moshrefyfar, M., Zarezadeh, J., Moosavizadeh, S.M.A., 2021. Evaluation of applicability of expanded shale to produce lightweight aggregate as a replacement for commercial LECA in constructions. Q. J. Eng. Geol. Hydrogeol. 54 (4) pp.qjegh2020-176.
Uslu, İ., Uysal, O., Aktaş, C.B., Chang, B., Yaman, İ.Ö., 2024. Dematerialization of Concrete: Meta-Analysis of Lightweight Expanded Clay Concrete for Compressive Strength. Sustainability 16 (15), 6346.
Wang, W., Emamjomehzadeh, O., Leitão, J.P., Juma, B., Wang, Z., Guan, M., Saksena, S., Zarei, S., Wani, O., 2026. Next-Generation Stormwater Infrastructures: A Typology of Paradigms for Design and Operation. Wiley Interdiscip. Rev. Water 13 (1), e70058.
Westholm, L.J., 2023. Filter media for storm water treatment in sustainable cities: A review. Front. Chem. Eng. 5, 1149252. https://doi.org/10.3389/fceng.2023.1149252.
Zhang, C., Hu, M., Pohjalainen, E., Di Maio, F., Stegemann, J.A., 2026a. Enhancing the uptake of secondary raw materials in the construction sector through reuse and recycling. Chem. Circ. 1 (1).
Zhang, X., Sun, D., Guo, S., Jiao, W., Zhang, H., Zhang, Z., Li, H., 2026b. Mechanisms of enhanced pollutant removal and microbial adaptation in stormwater infiltration systems with construction wastes as key fillers. J. Water Process. Eng. 84, 109757.
Zhou, H., Gao, C., Luan, Q., Shi, L., Lu, Z., Liu, J., 2024. Multi-objective optimization of distributed green infrastructure for effective stormwater management in space-constrained highly urbanized areas. J. Hydrol. 644, 132065.
Zhou, M., Wu, S., Zhang, Z., Aihemaiti, Y., Yang, L., Shao, Y., Chen, Z., Jiang, Y., Jin, C., Zheng, G., 2022. Dilution or enrichment: the effects of flood on pollutants in urban rivers. Environ. Sci. Eur. 34 (1), 61.