

# Minimax-Based Evaluation of Layered Natural and Waste-Derived Media Filtration for On-Site Greywater Treatment and Reuse

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## Abstract

Passive filtration through granular and fibrous media is the treatment route most often proposed for household-scale greywater reuse, and a recurring design proposition holds that arranging complementary media in layers delivers performance beyond that of the constituent media. This review tests that proposition rather than restating it. A structured search of an open scholarly index and the Crossref registry, executed without a relevance ceiling or date restriction and supplemented by backward and forward citation chasing of every included primary study, returned 16,879 records that reduced to 9,566 unique records after deduplication. Two-stage screening yielded 73 primary studies, classified into four evidence tiers by matrix and system type and into seven comparator types according to the causal effect each design can estimate. The central finding is negative and specific: no study compares a layered configuration with its constituent media at matched bed depth, media mass and contact time, so the benefit attributable to layering, as distinct from added depth and residence time, has never been estimated. What the evidence does support is narrower: adding an adsorptive carbonaceous stage to a straining bed improves removal of dissolved organics, surfactants and micropollutants, consistently in direction across independent groups; substituting a pyrogenic carbon for sand improves organic and, more modestly, microbial removal; and pyrolysis rather than botanical origin accounts for most of the performance of lignocellulosic residues. Against this, mixing media degraded most endpoints in the one study that tested mixtures, and several organic media leach dissolved organic carbon. Loading effects are endpoint-specific: organic removal is robust in generously sized beds, whereas microbial removal declines consistently as loading rises. Faecal-indicator reductions span roughly 0 to 3 log<sub>10</sub> in granular beds, viral data are sparse, and risk-based studies find residual viral risk after filtration alone. Media filtration should therefore be specified as one barrier within a multiple-barrier train, and the depth-matched factorial experiment required to resolve the field's central design claim is set out.

**Keywords:** *Greywater; on-site treatment; granular media filtration; layered filter design; biochar; activated carbon; hydraulic loading rate; pathogen barrier; water reuse; evidence appraisal.*

## 1. Introduction

### 1.1. Background

Greywater, the fraction of domestic wastewater from bathing, hand basins, laundry and, depending on definition, kitchen sinks, is simultaneously the largest and least contaminated component of household wastewater: one detailed characterisation places it at up to three quarters of domestic wastewater volume while contributing only about one third of its organic load [1]. That asymmetry is the structural reason greywater attracts attention as a reuse resource, since a large stream can be reclaimed for non-potable purposes at a lower treatment burden than mixed sewage. The case is strongest where sewerage is absent or partial, and field measurements in urban Ghanaian settings show generation of roughly 52 to 54 L per capita per day recovered at the point of demand [2].

Among on-site treatment options, passive filtration through packed beds of granular or fibrous media occupies a distinctive position: gravity-driven operation needs no external energy, the materials are locally available, and construction and maintenance need no specialist skills. These attributes explain its persistence in the low- and middle-income-country literature alongside constructed wetlands and other nature-based systems [3,4]. Within this literature a specific proposition has become close to conventional: that arranging several media with different dominant removal mechanisms in series

within a single column, typically gravel and sand for straining, a pyrogenic or activated carbon for adsorption, and a lignocellulosic fibre for surfactant retention and biofilm support, produces a system whose performance exceeds that of its constituents. The proposition is intuitive and mechanistically plausible. It is also, as this review shows, rarely tested in a way that could establish it.

### 1.2. Existing reviews and the state of knowledge

Capable reviews already cover parts of this field, including greywater characterisation and its variability [5], biological treatability [6], organic filter materials [7] and sand-based filtration for micropollutants [8]. Two are directly comparable. A review of granular media filtration for on-site greywater treatment maps media characteristics, size, depth, operating conditions, pre-treatment and guideline compliance [9]. A systematic review of biochar-based column filtration identifies 28 studies across 16 countries, distinguishes single, multilayer and polishing configurations, and reports removal efficiencies of 50 to 99% [10]. A recent meta-analysis of green walls further demonstrates that quantitative synthesis is achievable where data are structured, deriving load-removal regressions from more than 8,500 entries and advising a disinfection unit for reuse [4]. Table 1 positions the present review against these predecessors by stated scope.

**Table 1. Position of the present review relative to the most directly comparable predecessors.**  
Judgements refer to each work's stated scope, not its quality.

| Review                      | Scope as stated                                                                                                                | Isolates the causal effect of layering                              | Explicit evidence-quality appraisal                    | Scenario-specific reuse benchmarks                          |
|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|-------------------------------------------------------------|
| Shaikh and Ahammed [9]      | Granular media filtration for on-site greywater: media, size, depth, operating conditions, pre-treatment, guideline comparison | No; configurations described, effect not estimated                  | No                                                     | Comparison against guideline values                         |
| Bautista Quispe et al. [10] | Systematic review of biochar-based column filtration; 28 studies; single, multilayer and polishing configurations              | No; multilayer catalogued as a configuration class                  | Partial, through systematic selection                  | No                                                          |
| Galvao et al. [4]           | Meta-analysis of green walls for greywater; 33 studies, more than 8,500 entries; load-removal regressions                      | No                                                                  | Yes, through quantitative synthesis                    | Disinfection advised for reuse                              |
| Arden and Ma [3]            | Constructed wetlands for greywater against water-quality standards                                                             | No                                                                  | No                                                     | Standards-based; microbiological standards not reliably met |
| Li et al. [8]               | Sand and sand-GAC filtration for pharmaceuticals and personal care products                                                    | Partial, for the sand versus sand-GAC contrast                      | No                                                     | No                                                          |
| Present review              | Layered and single-medium media filtration for greywater: design claims, evidence quality, reuse readiness                     | Yes, as the primary objective, with an explicit comparator taxonomy | Yes, with a published codebook and domain-level matrix | Yes, by named scenario and instrument                       |

### 1.3. Research gaps

Three gaps remain in this literature, and together they define the scope of the present review.

- Gap 1. The causal effect of layering has not been isolated. Neither directly comparable review separates the contribution of a layered configuration from the additional bed depth, media mass and

contact time that accompany it in every reported design; the multilayer configuration is catalogued as a class, but the effect attributable to it has not been estimated.

- Gap 2. The quality of the primary evidence has not been appraised explicitly. Neither review applies a structured assessment of controls, replication, matrix realism, duration or loading reporting, so short uncontrolled experiments carry the same apparent weight as factorially designed work.
- Gap 3. The evidence base has expanded substantially since 2022 and has not been synthesised. Controlled media comparisons [11,12], direct tests of layer number [13,14], long-duration monitoring [15,16] and studies bearing directly on the microbiological conclusion [17,18] all post-date the comparable reviews.

#### **1.4. Structure of the review**

Section 2 sets out the review methodology: information sources and search strategy, eligibility, screening and record flow, evidence tiers, the comparator taxonomy, the appraisal codebook and the synthesis approach. Section 3 characterises greywater as a treatment feedstock, and Section 4 examines each media class and the removal functions attributed to it. Section 5 addresses the layering claim directly, Section 6 the hydraulic and operational determinants of performance, Section 7 microbiological performance and the limits of filtration, and Section 8 surfactants and micropollutants. Section 9 assesses reuse readiness against benchmarks and the receiving environment, and Section 10 positions media filtration among competing on-site technologies. Section 11 presents the critical analysis of the evidence base, Section 12 the prioritised future research agenda, Section 13 the limitations of the review and Section 14 the conclusions.

## **2. Review Methodology**

### **2.1. Review type, and what it does and does not claim**

This is a purposive critical review with a structured, documented and archivable search. It is not a systematic review or meta-analysis, and the distinction governs how its numbers should be read. The search is designed for comprehensiveness within a defined topic boundary rather than exhaustive enumeration, and screening and appraisal were performed by a single analyst. Every count reported here therefore describes the assembled corpus, not the literature as a whole; where reasoning would require a population estimate, the claim is made qualitatively instead. Reporting follows the grouping and effect-direction logic of Synthesis Without Meta-analysis, and the record flow is shown in the PRISMA style in Figure 1 for auditability, without claiming systematic-review status.

### **2.2. Information sources and search strategy**

Three discovery routes were used on 26 August 2026. First, the works endpoint of an open scholarly metadata index was queried with 22 search strings covering greywater characterisation, media filtration and its constituent media classes, layered configurations, comparator technologies, microbiological risk, reuse regulation, service life and bibliometric context, using cursor pagination to exhaustion or a ceiling of 600 records per query; no relevance ceiling and no publication-date filter were applied, and the total matching and retrieved counts for every query are given in Supplementary File S2a. The date restriction used in an earlier version was removed because mechanism, maturation and service life are central concerns here, and the corpus consequently extends from 1991 onward. Second, Crossref was queried independently with 16 paginated bibliographic searches. Third, every primary study retained after screening was resolved to its identifier in the same index and both its reference list and the works citing it were retrieved in full, yielding 1,192 forward and 2,019 backward records. The three routes returned 8,868, 4,800 and 3,211 records respectively, 16,879 in total; within-source deduplication left a combined pool of 10,665.

### **2.3. Eligibility criteria**

Eligibility was specified before screening in terms of matrix, intervention, comparator and outcome. A record was eligible as a primary study if it reported original quantitative water-quality data for treatment of greywater, or a defined greywater fraction, by a packed bed of granular or fibrous media. Studies using synthetic greywater, proxy wastewaters or non-packed-bed systems were not excluded but assigned to lower evidence tiers, because they carry mechanistic information the direct evidence does not supply. Records were eligible as supporting evidence if they provided characterisation, review-level synthesis, microbial risk assessment, or regulatory, environmental-fate, economic or bibliometric material. Records were excluded where the matrix was industrial wastewater or unqualified sewage outside the analogue tiers, where no filtration or sorption medium was involved, where no quantitative outcome was reported, or where the record was not a peer-reviewed journal article. No language

restriction was applied at the search stage; all records meeting the criteria were in English, recorded as a limitation in Section 13. One record was excluded on internal-consistency grounds: a study reporting sand columns of 40 to 100 feet in a bench-scale apparatus, a geometry inconsistent with its described method.

#### 2.4. Screening, deduplication and record flow

Cross-source deduplication used two passes: normalised digital object identifiers reduced the pool from 10,665 to 9,739 records, and a second pass on punctuation-stripped, case-folded titles identified 109 clusters in which one work carried more than one identifier, leaving 9,566 unique records. Title screening applied a documented rule: a record was retained if its title contained a greywater term, or both a media or filtration term and a water, wastewater or reuse context term. This retained 2,097 records (1,212 naming greywater; 885 analogue candidates) and set aside 7,469. Full title-and-abstract screening against the eligibility criteria included 134 of the 2,097 and excluded 1,963. Because the mechanical rule is tuned to find packed-bed greywater studies, a further 11 records covering reuse regulation, microbial risk, bibliometrics and drinking-water analogues were retained on the basis of the topic-specific query that had retrieved them, screened against the same criteria, and identified as such in Supplementary File S3. Together these give 145 included journal articles, of which 73 are primary studies, 31 are reviews and syntheses and 41 are supporting records; five standards and guidance documents used in Section 9 are additional to the search. Screening was performed by a single analyst, so no inter-rater agreement statistic can be reported. Every included article was verified against its Crossref registration, from which all bibliographic elements were taken. In accordance with the reference limit of the target journal, the reference list of this article is confined to the works discussed directly in the text and carries a digital object identifier for every journal article; the complete list of included works with identifiers, including all 73 primary studies, is provided in Supplementary Files S1 and S4.

#### 2.5. Evidence tiers

Because the corpus combines real-greywater packed beds with synthetic-greywater columns, vegetated systems, batch sorption experiments and drinking-water analogues, and because these do not address the same problem, each of the 73 primary studies was assigned to one of four tiers (Table 2): 23 in Tier A, 10 in Tier B, 29 in Tier C and 11 in Tier D. Tier reflects the distance between a study's matrix and system and the objective of this review, not experimental quality; several Tier C and D studies are among the most rigorously controlled work in the field precisely because their matrix is held constant, and the text says so wherever such a study is used. Conclusions are stated from Tier A first, with lower tiers used for mechanism or transferability and labelled with an explicit downgrade for indirectness.

**Table 2. Evidence tiers. Tier reflects distance from the review objective, not experimental quality.**

| Tier | Definition                                                                                                                                                                  | Studies | What it can support                                                                  |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|--------------------------------------------------------------------------------------|
| A    | Real greywater, or a defined real fraction, in a packed granular or fibrous bed with an internal comparator isolating a media, configuration, geometric or operating effect | 23      | Direct conclusions about media and configuration performance for greywater           |
| B    | Real greywater in a packed bed without such a comparator                                                                                                                    | 10      | Absolute effluent quality achievable; not attribution to any component               |
| C    | Synthetic greywater in packed beds; real greywater in non-packed-bed systems (vegetated walls and roofs, batch sorption, membrane-coupled trains)                           | 29      | Mechanism, controlled contrasts and dose-response; transferability requires argument |
| D    | External analogues: municipal, diluted or tertiary wastewater, drinking-water filters, single-solute model systems                                                          | 11      | Mechanism and physical principles only; downgraded whenever used                     |

#### 2.6. Comparator taxonomy and the causal estimand

Objective 2 requires a defined estimand, because three distinct quantities are conflated in this literature: the incremental benefit of adding an adsorptive stage to an existing bed; the superiority of a layered configuration over each constituent at equal size; and interaction, a joint effect exceeding the sum of

stage effects. Only the second and third are properly layering benefits, and only a comparator holding total bed depth, media mass, empty-bed contact time, loading and influent constant can estimate them. Every primary study was therefore classified by comparator type (Figure 2): CT1, depth- and contact-time-matched constituent control; CT2, unmatched added-stage control; CT3, media substitution at constant geometry; CT4, process staging; CT5, hydraulic or geometric comparison; CT6, media mixing or amendment; CT0, none. The distribution across the 73 studies is 0, 5, 26, 9, 17, 5 and 11. Terminology throughout follows this classification: "media substitution", "added adsorptive stage" and "integrated treatment train" describe what CT3, CT2 and CT4 designs estimate, while "layering benefit" and "synergy" are reserved for designs that can exclude bed-depth and residence-time explanations.

## **2.7. Data extraction and appraisal codebook**

For each primary study we extracted matrix and its realism; media composition, configuration, depth and grain size; comparator type; scale; duration; hydraulic and organic loading as reported and converted to a common basis; influent and effluent concentrations; variance and replication; sampling frequency; whether disinfection preceded the reported sample; and outcomes across organic, solids, nutrient, surfactant, micropollutant and microbial endpoints (Supplementary File S4). Appraisal used five domains with operational definitions published in Supplementary File S5: control adequacy, replication and variance, matrix realism, duration adequacy relative to the mechanism inferred (one year for adsorptive service life; thirty days for biological maturation), and loading completeness with correct dimensions. Each domain was scored adequate, inadequate or unclear. Unclear denotes that the accessible record does not report the domain; it is treated as missing information, not as evidence of poor conduct, and studies scored unclear are excluded from the denominator for that domain. This corrects an earlier error of interpretation in which absence of reporting was treated as absence of practice.

## **2.8. Synthesis approach and the feasibility of quantitative pooling**

Whether quantitative synthesis is possible was assessed rather than assumed. Three obstacles were identified: influent strength across the corpus spans more than an order of magnitude, and percentage removal is mathematically dependent on influent concentration; loading is reported in at least six mutually inconvertible unit systems, with organic loading frequently absent; and dispersion and replication are unreported for a large share of the corpus. A pooled analysis of percentage removals was therefore judged inappropriate. Two narrower analyses are feasible in principle and are recommended in Section 12 rather than executed on abstract-derived data: meta-regression of effluent concentration on areal mass load, already demonstrated for the vegetated subset [4], and pooled  $\log_{10}$  microbial reduction within granular beds. Synthesis here is structured but qualitative, organised by endpoint and effect direction, with absolute effluent quality reported alongside percentages wherever the source permits.

## **2.9. Reproducibility and archiving**

Queries, endpoints, pagination, filters, deduplication and screening rules are specified above and in Supplementary Files S2a to S5, which contain the search log, the deduplicated record set, screening decisions, the extraction dataset and the appraisal codebook, so the corpus can be reconstructed record by record. Because database coverage and relevance ranking change over time, the archived record set rather than the query string is the reproducible artefact. The authors should deposit these files in an open repository and cite the versioned identifier in the data-availability statement before submission.

# **3. The treatment problem: greywater composition and its consequences**

## **3.1. Variability is the design constraint**

The dominant characteristic of greywater as a feedstock is not its average composition but its variability. The most comprehensive characterisation review finds that quantity and quality vary widely with time and source, and that treatment selection depends primarily on that variability [5]. Two studies from one Ghanaian city illustrate the scale. Combined greywater from a campus neighbourhood carried five-day biochemical oxygen demand ( $\text{BOD}_5$ ) of 320 to 350  $\text{mg L}^{-1}$ , chemical oxygen demand (COD) of 690 to 740  $\text{mg L}^{-1}$ , turbidity near 270 NTU and 6 to 7  $\text{mg L}^{-1}$  of linear alkylbenzene sulfonate (LAS), with a  $\text{BOD}_5$  to COD ratio of about 0.5 and a sodium adsorption ratio of only 0.6 [2]. Composite handwashing greywater from five schools was of comparable strength, with mean COD of 999.9  $\text{mg L}^{-1}$  and turbidity of 278.9 NTU, yet school-level turbidity spanned 40 to 265 NTU and  $\text{BOD}_5$  118 to 226  $\text{mg L}^{-1}$ , so variation between five sites of a single type was itself substantial [18]. The full range of influent strengths across the 73 primary studies, from about 50 to about 1,000  $\text{mg L}^{-1}$  COD for domestic

greywater, is tabulated in Supplementary File S4; commercial laundry effluent, an order of magnitude stronger again, is a distinct matrix and is excluded from the domestic ranges quoted in this review.

### **3.2. Biodegradability is not a fixed property**

The BOD<sub>5</sub> to COD ratio is often used as a design parameter, low values indicating a recalcitrant fraction requiring adsorption rather than biological treatment. The ratio itself is highly variable, and the causes are chemical. Personal care products contribute organic carbon differing by more than an order of magnitude between categories, from about 0.2 g total organic carbon per litre for hair conditioners to 2.7 g L<sup>-1</sup> for toothpastes, and contribute little macronutrient content, which limits biological treatability [1]. Light greywater from bathing and hand washing generally requires nutrient supplementation for aerobic biodegradation, whereas darker fractions carry sufficient nutrients, and LAS may inhibit anaerobic pathways [6]. Two consequences follow: surfactant load determines whether the biological component of a filter functions at all, and single grab-sample characterisation is inadequate for design.

### **3.3. Source separation changes loading more than concentration**

Excluding the kitchen fraction is routinely recommended, and the evidence supports it for a more specific reason than usually stated. In a household-scale system monitored over 1,330 days, removing the kitchen component halved influent BOD<sub>5</sub> without a corresponding fall in COD, and cut applied hydraulic loading from about 114 to 35 mm d<sup>-1</sup>; the principal benefit was reduced organic flux, clogging and maintenance rather than transformed effluent chemistry [19]. Risk analysis is consistent: treated bathroom and laundry greywater met infection-risk and disease-burden benchmarks for food-crop irrigation, and kitchen greywater did not [20].

### **3.4. Percentage removal is a weak basis for comparison**

A filter producing 30 mg L<sup>-1</sup> effluent BOD<sub>5</sub> reports 90% removal on a 300 mg L<sup>-1</sup> influent and 40% on a 50 mg L<sup>-1</sup> influent, despite delivering identical effluent quality. Because domestic influent strengths in this corpus span more than an order of magnitude (Section 3.1), reported percentages are not commensurable, and media rankings built from them are unreliable. This is the principal reason quantitative pooling was rejected (Section 2.8), and it motivates the mass-flux reporting standard proposed in Section 12.

## **4. Media classes and their attributed functions**

### **4.1. Sand and gravel: the reference media, weak for dissolved organics**

Sand is efficient for particulates and, once biologically mature, for microbial retention, but poor for dissolved organic carbon: a replicated column study on artificial greywater removed 51 to 60% of volatile solids but only 26.8% of COD (Tier C) [21], consistent with sand's low sorption capacity, which leaves dissolved-organic removal dependent on biodegradation [8]. Performance is nonetheless strongly modifiable by geometry and hydraulics. In the most complete Tier A treatment, three sand gradings were run at three flow rates on real greywater: fine sand at 320 L m<sup>-2</sup> d<sup>-1</sup> removed 99% of turbidity, 94% of BOD<sub>5</sub> and 95% of COD with 1.65 log<sub>10</sub> faecal coliform reduction, and optimisation identified 0.68 mm and 470 L m<sup>-2</sup> d<sup>-1</sup> [16]. Gravel serves mainly as support and pre-filtration, and it served as the reference medium in the anaerobic filter comparisons discussed below [22].

### **4.2. Pyrogenic carbon: the best-evidenced substitution, with bounded gains**

Biochar carries the strongest controlled evidence, from matched comparisons on proxy matrices. In anaerobic filters fed municipal sewage at 0.05 m h<sup>-1</sup>, biochar significantly outperformed woodchip and gravel for COD, organic carbon, turbidity and faecal indicators, reaching 90% COD removal and 1.7 log<sub>10</sub> indicator reduction (Tier D) [22]. In a slow-sand configuration at the same loading, *Miscanthus* biochar achieved COD removal of 74 ± 18% against 61 ± 12% for sand and *Escherichia coli* removal of 1.35 ± 0.27 against 1.18 ± 0.31 log<sub>10</sub>, both significant (Tier D) [23]. Read precisely, both used sewage rather than greywater, the COD advantage is about thirteen percentage points, and the microbial advantage is about 0.17 log<sub>10</sub> with overlapping standard deviations: the direction is robust, the magnitude incremental, and narratives presenting biochar substitution as transformative are not supported by the studies most often cited for them. Complementary work shows COD removal above 90% across biochar types, particle sizes of 0.7 to 2.8 mm and a fourfold loading range, with phosphorus removal declining after two months and total nitrogen removal exceeding sand (Tier D) [24]. In greywater itself, a field biochar filter removed 93% of BOD<sub>5</sub> and 85% of solids (Tier B) [25], and the systematic review of biochar columns reports 50 to 99% removal across 28 studies while identifying long-term assessment and additional microbial indicators as unmet needs [10].

### **4.3. Activated carbon: highest capacity, finite service life**

Activated carbon generally outperforms biochar for bulk organics and anionic surfactants, but not uniformly: a Tier A comparison on real greywater found activated carbon superior for COD and anionic surfactants while woodchip biochar showed higher affinity for non-ionic surfactants, activated carbon offering delayed breakthrough and biochar faster, cheaper uptake [11]. That no single carbonaceous medium dominates across the pollutant spectrum is itself the mechanistic premise on which media diversification rests. The balance of adsorption and biodegradation depends on design and history rather than the medium: in a biologically active granular activated carbon (GAC) system, biodegradation contributed under 26% of treatment [26], whereas in a biological GAC filter run beyond 900 days on membrane-bioreactor effluent, sorption and biodegradation were of comparable importance throughout, biodegradation dominating the upper bed while residual sorption capacity below buffered influent peaks [15]. Short experiments on strong influent are sorption-dominated; long operation on low-carbon influent lets the biological contribution develop as the sorption front advances. Configuration also matters: dividing a bed into unsaturated and saturated zones sustained 94% COD removal for 253 days at high loading [27], and a GAC layer sandwiched within a coarse sand filter removed 98.2% of four pharmaceuticals, significantly better than single-sand and single-GAC controls (Tier D) [28].

#### **4.4. Lignocellulosic residues: promising, weakly controlled, prone to leaching**

The clearest positive result is a Tier A comparison of raw coconut husk, pyrolysed coconut husk and a sand-gravel control under identical conditions: turbidity removal rose from 63% raw to 95% pyrolysed, nitrate removal was 78.9, 88.4 and 28.7% respectively, and faecal coliform removal for the pyrolysed material reached 2.87 log<sub>10</sub>, two orders of magnitude above the raw fibre [29]. Pyrolysis, not botanical origin, accounts for most of the performance. Mulch-type media achieve BOD<sub>5</sub> reductions of 55 to 99.9%, bark, peat and woodchips outperforming sand under comparable conditions [7]. The recurring failure mode is leaching: release of filter material with increased effluent COD is recorded for some mulches [7], spent coffee grounds produced higher effluent than influent BOD<sub>5</sub> in a controlled five-substrate comparison [30], and soil and coco-coir media leached organic matter in a hyper-arid green wall while a charcoal-based medium removed 97% of turbidity and 90% of ammonium without doing so [12]. Three independent reports thus converge: an insufficiently stabilised organic medium can be a source of dissolved organic carbon rather than a sink, and the early weeks in which it happens are exactly when household users judge whether a system works.

#### **4.5. Mineral and waste-derived media, and the salinity trade-off**

One Tier A field comparison exposes a trade-off that percentages conceal. Six granular systems, each serving a rural Jordanian household for about thirteen months, compared volcanic tuff with gravel: tuff removed more organic matter and solids (73, 65 and 85% for BOD<sub>5</sub>, COD and total suspended solids against 49, 51 and 76%) but significantly raised effluent electrical conductivity, sodium, chloride, sodium adsorption ratio and exchangeable sodium percentage, leading the authors to prefer gravel's less concentrated effluent [31]. For irrigation, the better-performing medium on conventional indices was the worse choice on the indices governing soil suitability. Granulated blast-furnace slag compared against sand and activated carbon achieved 1.96 to 2.30 log<sub>10</sub> faecal coliform reduction [32].

#### **4.6. Amendments: more is not necessarily better**

Graphene at 5% by volume in a coir, perlite and biochar green-wall medium produced no significant overall improvement, with a detectable benefit only in the first of three levels [33], and physically mixing media degraded most endpoints in the one study to test mixtures directly (Section 5.6) [34]. Interaction effects are not predictable from component properties in isolation, which is the core weakness of additive reasoning about media assemblages.

### **5. The layering claim: what the evidence can establish**

#### **5.1. Defining the estimand**

Adding a layer to an otherwise unchanged column increases bed depth, media mass and empty-bed contact time along with media diversity, so an improvement over the unmodified column estimates only the incremental benefit of an added stage. A layering benefit proper means either that a divided bed outperforms each constituent at equal size, or that media interact so that the whole exceeds the sum of its stages, and only a comparator holding depth, mass, contact time, loading and influent constant can estimate either. An earlier version of this work reported how many studies included "a control or parallel comparison"; that statistic pools comparators estimating different effects and is uninformative for the present objective. The corpus was therefore reclassified by comparator type (Section 2.6), and the result, summarised in Figure 2, is the principal finding of this review.

## 5.2. The principal finding: the identifying comparison has not been made

None of the 73 primary studies provides a CT1 comparison: no study compares a layered configuration against its constituent media at matched total bed depth, media mass and contact time, on any greywater matrix. The distribution is instead 26 media substitutions, 17 hydraulic or geometric comparisons, nine staging comparisons, five unmatched added-stage comparisons, five mixing designs and 11 studies with no comparator. The consequence should be stated plainly: the benefit attributable to layering as such has never been estimated for greywater filtration. This is not a claim that layering does not work; it is a claim that the field has not performed the experiment its design guidance presupposes. The confounding is material, not theoretical: increased bed height improved performance in a controlled media study [34], and depth was one of three governing variables in the most complete sand-filter optimisation [16]. Where a layered column beats a shallower single-medium column, greater depth alone is a sufficient alternative explanation that the reported data cannot exclude.

## 5.3. What the added-stage evidence does support

The five CT2 designs consistently support the weaker quantity: adding an adsorptive stage to a bed that lacks one improves treatment. The most direct is a Tier A study on real handwashing greywater from five Ghanaian schools, operating a sand-only control against sand with 50 mm and with 85 mm of GAC in parallel for 28 days. The deeper-carbon arm performed best, removing 89.0% of turbidity, 91.2% of suspended solids, 85.7% of COD, 90.1% of Salmonella and 98.3% of total coliforms, significantly better than the control ( $p \leq 0.041$ ); yet total depth was not equalised, so the added carbon cannot be separated from the added depth carrying it [18]. A laboratory comparison of gravel-sand against gravel-sand-GAC across three retention times lifted the worst-parameter lower bound from 47.2 to 60.8% [35], the practically decisive change since the worst parameter determines fitness for reuse. In the analogue literature, the GAC sandwich filter removed 98.2% of four pharmaceuticals, significantly better than single-sand and single-GAC controls, again without equalised depth (Tier D) [28], and in textile media, adding a woven cotton layer raised soluble COD removal from below 3% to  $28.1 \pm 4.3\%$  [36]. Figure 3 places the organic-removal values of the greywater studies within the corpus-wide distribution. The direction is consistent across four independent groups, three matrices and two media classes; what it supports is that adsorptive capacity added to a bed lacking it improves removal of the dissolved fraction straining media cannot address, a weaker statement than the design literature usually makes.

## 5.4. Media substitution is well evidenced, and is not layering

The 26 CT3 designs are the largest and best-evidenced group, and their findings are frequently cited in support of layered design although they address a different matter: biochar for sand or gravel [22,23], pyrolysed for raw husk [29], activated carbon for biochar with reversal for non-ionic surfactants [11], and tuff for gravel with a salinity penalty [31] are all statements about which medium to use, not how many or in what order. Reading them as evidence for layering is a category error common enough to warrant explicit correction.

## 5.5. Direct tests of configuration and layer number

The closest approach to a direct test comes from one experimental programme. Forty-nine configurations of silica sand gradings and activated carbon were compared on synthetic greywater: three-layer filters performed best, but mean COD and conductivity removal across all configurations was only 36.3 and 15.1%, the optimised design reaching 72 and 30% (Tier C) [13]. With upstream coagulation added, a three-stage configuration reached 90.8% COD and 98.9% turbidity removal [14], the gain attributable to the coagulation step rather than the filter. Three points follow: configuration matters and layer number is not irrelevant; thickness varied with layer number, so depth is again unmatched and the comparisons remain CT6 rather than CT1; and the filters' standalone performance, averaging 36.3% COD removal, is far below the values typically quoted for multi-layer natural filters, a useful corrective to expectations set by single-configuration reports. A hybrid multi-layer slow sand filter coupled to microfiltration and ultrafiltration reached 98.2% COD and 99.97% LAS removal over 157 days, but as a CT4 train the filter's contribution cannot be separated from the membranes' [37].

## 5.6. Where combining media does not help

The five CT6 designs are the only ones able to detect interaction, and their results are mostly unfavourable to additive reasoning. The most direct test compared six individual media and then mixtures: the date-seed and spent-coffee-ground mixture drained best, but most pollutants deteriorated slightly on mixing, only solids and COD improving [34]. Graphene amendment produced no significant overall improvement [33], and organic media can be net carbon sources [7,30,12]. A layer chosen for its sorption capacity can worsen the parameter it was meant to improve.

## 5.7. Sensitivity of the conclusions to evidence tier

Because tier assignment could in principle drive the conclusions, each substantive claim was re-examined under progressive exclusion of lower-tier and less complete evidence (Table 3). Excluding Tier D leaves 62 studies; excluding Tiers C and D leaves 33; further excluding studies whose outcomes were not extractable leaves 21; further excluding those without an internal comparator leaves 17. Three claims survive every exclusion: that no CT1 comparison exists; that an added adsorptive stage improves dissolved-fraction removal, resting at the last step on three Tier A studies [18,35,36]; and that substitution effects are real and direction-consistent, resting on three others [29,11,31]. One claim does not: the mixing penalty rests on a single Tier C study with no Tier A or B test, and is reported throughout as provisional.

**Table 3. Sensitivity of the principal Section 5 conclusions to progressive exclusion of lower-tier and less complete evidence.**

| <b>Exclusion applied</b>              | <b>Studies remaining</b> | <b>No CT1 comparison exists</b> | <b>Added adsorptive stage improves dissolved-fraction removal</b> | <b>Substitution effects real and direction-consistent</b> | <b>Mixing degrades most endpoints</b> |
|---------------------------------------|--------------------------|---------------------------------|-------------------------------------------------------------------|-----------------------------------------------------------|---------------------------------------|
| None (full corpus)                    | 73                       | Holds                           | Holds                                                             | Holds                                                     | Holds, single study                   |
| Exclude Tier D                        | 62                       | Holds                           | Holds                                                             | Holds                                                     | Holds, single study                   |
| Exclude Tiers C and D                 | 33                       | Holds                           | Holds                                                             | Holds                                                     | Fails: no Tier A or B test            |
| Also exclude outcomes not extractable | 21                       | Holds                           | Holds                                                             | Holds                                                     | Fails                                 |
| Also exclude no internal comparator   | 17                       | Holds                           | Holds on three Tier A studies                                     | Holds on three Tier A studies                             | Fails                                 |

## 5.8. Synthesis

The controlled evidence supports a narrower proposition than the one commonly advanced. Combining a straining medium with an adsorptive carbonaceous medium reliably improves removal of dissolved organic carbon, surfactants and micropollutants, mechanistically explicable because sand sorbs these fractions poorly [8,28]. It does not establish that performance rises with layer number, that any medium is superior across endpoints, or that layering resolves the microbiological constraint of Section 7; and where media are mixed rather than layered, the limited evidence points to a small penalty. Media selection should be driven by the pollutant fraction limiting the intended reuse, and by bed depth and contact time, rather than by the accumulation of layers.

## 6. Hydraulic and operational determinants of performance

### 6.1. Loading rate: an endpoint-specific effect

The literature contains apparently flat contradictions about loading sensitivity that dissolve when results are read by pollutant class (Table 4). For bulk organic matter, sensitivity depends on bed sizing relative to applied load. Biochar filters held COD removal at 94 to 95% across hydraulic loading of 32 to 200 L m<sup>-2</sup> d<sup>-1</sup> and organic loading of 5 to 20 g BOD<sub>5</sub> m<sup>-2</sup> d<sup>-1</sup> (Tier D) [24]; a biological GAC filter showed no significant influence of contact time on organic removal over 900 days, attributed to generous bed sizing [15], with constant and intermittent flow indistinguishable and concentration peaks buffered by sorption [38]; biochar held effluent BOD<sub>5</sub> at 2 mg L<sup>-1</sup> across all rates in a five-substrate comparison while hemp and pumice deteriorated [30]; and a multistage wetland maintained 90% COD removal at about 90 g COD m<sup>-2</sup> d<sup>-1</sup> [19]. The opposite appears in organically overloaded beds: across 3.15 to 19.28 g COD L<sup>-1</sup> d<sup>-1</sup>, rising load reduced removal of COD, surfactants, solids and turbidity alike [37], and increased hydraulic loading reduced performance for every medium in the six-media comparison [34]. The supportable generalisation is conditional: organic removal is robust where the bed is large relative to the organic flux and sensitive where it is not.

For microbial removal the pattern is consistent and unfavourable. Feeding biochar columns at one, six and twelve times design loading cut bacterial removal from 2-4 to 1 log<sub>10</sub> and viral removal from 2 to 0.8 log<sub>10</sub>, effective grain size becoming the dominant variable (Tier D) [39]; a pilot wetland roof performed best overall at 67 to 80 L m<sup>-2</sup> d<sup>-1</sup> but 45 L m<sup>-2</sup> d<sup>-1</sup> was advised where pathogen removal governs [40]; and infiltration rate and event size significantly influenced *Escherichia coli* removal across 80 biofilter columns [41]. A loading rate optimised on organic criteria will therefore under-deliver on pathogens. For micropollutants the response is threshold-like: no significant difference between 10 and 20 cm h<sup>-1</sup> in GAC sandwich filters, but 5 cm h<sup>-1</sup> proved inapplicable because ammonium accumulated to 0.76 mg L<sup>-1</sup> [28]; slower is not uniformly better.

**Table 4. Reported effects of hydraulic and organic loading, arranged by endpoint. Contradictions in the literature resolve when results are read by endpoint and by the ratio of bed size to applied load.**

| Study, system and tier                               | Loading range                                                                                      | Organic response                                                                                | Microbial response                                                                                                 |
|------------------------------------------------------|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Biochar filters, onsite wastewater [24] (D)          | 32-200 L m <sup>-2</sup> d <sup>-1</sup> ; 5-20 g BOD <sub>5</sub> m <sup>-2</sup> d <sup>-1</sup> | COD 94-95%, uninfluenced by loading                                                             | Not reported                                                                                                       |
| Biochar columns, diluted wastewater [39] (D)         | 1x, 6x, 12x design loading                                                                         | Not the focus                                                                                   | Bacteria 2-4 down to 1 log <sub>10</sub> ; viruses 2 down to 0.8 log <sub>10</sub> ; grain size dominant           |
| Green wall, five substrates, real greywater [30] (C) | 4.5, 9, 18 L d <sup>-1</sup>                                                                       | Biochar effluent BOD <sub>5</sub> stable at 2 mg L <sup>-1</sup> ; hemp and pumice deteriorated | Biochar 2.2-4.0 log <sub>10</sub> ( <i>E. coli</i> , enterococci)                                                  |
| Multi-layer slow sand filter with membranes [37] (C) | 3.15-19.28 g COD L <sup>-1</sup> d <sup>-1</sup>                                                   | Rising load reduced COD, LAS, solids, turbidity                                                 | Not reported                                                                                                       |
| GAC sandwich slow sand filter [28] (D)               | 5, 10, 20 cm h <sup>-1</sup>                                                                       | COD 65.8%; TOC 90.3% with 20 cm GAC                                                             | Not reported; 5 cm h <sup>-1</sup> inapplicable (ammonium accumulation)                                            |
| Pilot wetland roof, two years [40] (C)               | 45-80 L m <sup>-2</sup> d <sup>-1</sup>                                                            | BOD <sub>5</sub> above 96%; COD above 93%                                                       | <i>E. coli</i> 1.86 ± 1.54 log <sub>10</sub> ; 45 L m <sup>-2</sup> d <sup>-1</sup> advised where pathogens govern |
| Saturated sand filters, real greywater [16] (A)      | 320 L m <sup>-2</sup> d <sup>-1</sup> and equivalents; three media sizes                           | BOD <sub>5</sub> 94%; COD 95% (fine sand)                                                       | Faecal coliforms 1.65 log <sub>10</sub> ; optimum 0.68 mm, 470 L m <sup>-2</sup> d <sup>-1</sup>                   |

## 6.2. Depth, grain size and the location of removal

Depth and grain size are under-reported yet among the strongest determinants of performance. Depth-resolved experiments on full-scale slow sand filter material show removal is depth-integrated: retention rates in the top 5 cm exceed deeper material four- to five-fold, but the deeper layers, extending to about a metre, contribute more to overall log removal, the depth intervals together giving 1.4 to 1.7 log<sub>10</sub> for *Escherichia coli* and 0.4 to 0.6 log<sub>10</sub> for the bacteriophage PhiX 174 [42]. Household greywater filters, at a few tens of centimetres, forgo this contribution, which is why their microbial performance trails full-scale analogues. Grain size effects are equally consequential: effective particle diameter dominated microbial removal at elevated loading [39], and media size ranked with depth and flow rate in the sand-filter optimisation [16].

## 6.3. Operating mode, maturation and pre-treatment

Dividing a bed into unsaturated and saturated zones sustained 94% COD removal for 253 days [27]. Flow intermittency, often assumed problematic, was not: constant and intermittent operation gave indistinguishable organic removal, and influent peaks up to five times normal strength were buffered by sorption and released only afterwards [38]. Maturation is real but poorly bounded: biosand filters improved after 30 to 35 days [43], but no study determined the stabilisation point for a greywater filter, so the commonly quoted two-to-four-week commissioning period is convention rather than measurement. Pre-treatment governs run length, and in a household textile system the physical media

removed 96 to 98% of particulates but under 3% of soluble COD [36], separating the particulate from the dissolved fraction with unusual clarity.

#### **6.4. Service life: defining the endpoint that matters**

Elapsed time is not the transferable endpoint. What determines servicing is cumulative contaminant mass per unit mass of medium, expressed through breakthrough behaviour, bed volumes treated, head-loss development and explicit regeneration or replacement criteria; adsorptive exhaustion, hydraulic clogging and biological stabilisation are three processes with three timescales that the literature seldom separates. Only three studies in the corpus report continuous operation of eight months or more on real greywater in a packed bed of fixed configuration (Supplementary File S4), among them the thirteen-month Jordanian field comparison [31] and the 253-day carbon biofilter [27]. Four long observation periods do not transfer: the more-than-900-day carbon filter treated membrane-bioreactor effluent [15]; a twelve-month, 80-column study used synthetic greywater [41]; a two-year study was a vegetated roof [40]; and a household system described as running one year in fact comprised six consecutive 60-day runs with changing configurations, so it is not evidence of adsorptive service life [36]. Breakthrough has been characterised in columns [11] and residual sorption capacity shown to persist in a long-running bed [15], but no study determines the point of adsorptive exhaustion for any medium receiving raw greywater at household loading, or expresses it as a service interval. Durability claims for these systems are extrapolations, and are treated as such throughout this review.

### **7. Microbiological performance and the limits of filtration**

#### **7.1. Granular beds and vegetated biofilters are different distributions**

Microbial performance in this literature is not a single distribution, and pooling it produces the inconsistencies that summary ranges conceal; separating packed granular beds from vegetated biofilters resolves them (Figure 3). In packed granular beds treating real greywater, reported faecal-indicator reductions run from negligible to about 2.9 log<sub>10</sub>, with most central values between 1 and 2: a field biochar filter removed 93% of BOD<sub>5</sub> while *Escherichia coli* removal was insignificant [25]; optimised sand filters reached 1.65 log<sub>10</sub> [16]; sand, blast-furnace slag and activated carbon gave faecal coliform reductions of 1.11 to 3.68 and 1.96 to 2.30 log<sub>10</sub> [32]; pyrolysed coconut husk reached 2.87 log<sub>10</sub> [29]; and a sand-GAC filter removed 98.3% of total coliforms and 90.1% of Salmonella, about 1.8 and 1.0 log<sub>10</sub>, with residuals still above unrestricted-reuse thresholds [18]. A household textile system reported 99.59% *Escherichia coli* removal, but calcium hypochlorite was applied before reuse and the record does not state unambiguously whether the value precedes disinfection, so it is not used as filtration evidence [36]. Vegetated biofilters reach higher: biochar as a green-wall substrate gave 2.2 to 4.0 log<sub>10</sub> [30], and a twelve-month, 80-column study reported a median 3.0 log<sub>10</sub> *Escherichia coli* reduction meeting an indoor non-potable standard [41]. The class is not uniform, however: a green wall on real greywater removed more than 90% of organic parameters but only 1 log<sub>10</sub> of indicators, failing the applicable reuse guideline until electrochemical disinfection was added [44]. The analogue literature matches the lower figures, from biosand filters at 1.2 to 2.2 log<sub>10</sub> [43] through matched biochar-sand comparisons at 1.2 to 1.4 log<sub>10</sub> [23] and anaerobic filters at up to 1.7 log<sub>10</sub> [22] to 1.4 to 1.7 log<sub>10</sub> across the depth of a full-scale slow sand filter [42].

#### **7.2. Shallow household beds underperform their analogues**

Removal in slow sand filtration is depth-integrated rather than concentrated at the surface film: the schmutzdecke retains most efficiently per centimetre, but the metre of sand beneath it contributes more log removal in total [42]. Household beds of a few tens of centimetres cannot access that contribution. Immature filters underperform their steady state, since biosand performance improves over the first month [43], and loading compounds the limitation because microbial removal declines steeply with loading while organic removal often does not [39]. Where vegetated biofilters outperform granular beds, the designed saturated zone, longer residence time and plant-associated processes are the plausible mechanisms [41], none present in a simple layered column.

#### **7.3. Viral endpoints are sparse, and indicators do not substitute**

Nearly all microbiological reporting in this corpus uses *Escherichia coli* or faecal coliforms; four studies go further, and they matter disproportionately. Bacteriophage PhiX 174 removal in biochar columns fell to 0.8 log<sub>10</sub> at elevated loading [39]. In a controlled comparison of pine bark, activated charcoal and sand at three organic loading rates, *Escherichia coli* O157:H7 removal fell sharply in charcoal and sand when loading increased fivefold but rose by 2 log<sub>10</sub> in bark, and PhiX 174 behaved likewise, making bark the most promising medium for pathogen removal and showing that media rankings by bacterial

removal do not predict viral removal [45]. A carbon biofilter reported graded reduction across five surrogates including *Cryptosporidium* and *Giardia* oocysts [27], and depth-resolved slow-sand work quantifies the bacterial-viral gap directly, 1.4 to 1.7 against 0.4 to 0.6 log<sub>10</sub> in the same material [42]. Risk modelling reinforces the point: analysis of an anaerobic-filter and wetland plant concluded not only that post-treatment with sand filtration and chlorination was essential but that *Escherichia coli* is not an appropriate indicator for greywater reuse risk [46], a structural limitation of an evidence base that relies on it almost exclusively.

#### 7.4. Risk-based evidence

Quantitative microbial risk assessment converges with the treatment data. Where greywater is filtered but not disinfected, residual exposure to resistant agents remains: biochar filtration reduced the median annual Salmonella disease probability from  $1.39 \times 10^{-2}$  to  $6.0 \times 10^{-3}$  but left the rotavirus burden essentially unchanged, and identified ingestion during system maintenance as the dominant exposure route [25]; an anaerobic filter with a vertical wetland met the  $10^{-4}$  annual infection benchmark for *Campylobacter* and *Cryptosporidium* but not rotavirus [46]; bench sand-GAC filtration left school handwashing greywater above unrestricted-reuse thresholds [18]; and in a three-stage biochar-sand-chlorination system, filtration delivered the physicochemical treatment but chlorination was essential for complete microbial inactivation [17]. Where adequate treatment is applied, risk falls within benchmarks: greywater was safe for toilet flushing after microfiltration, and treated bathroom and laundry greywater met the  $10^{-4}$  infection-risk and  $10^{-6}$  disability-adjusted-life-year benchmarks for food-crop irrigation while kitchen greywater did not [20]; exposure modelling set best-practice thresholds of below 5 CFU per 100 mL for *Shigella* and 500 for *Salmonella enterica*, with treatment and disinfection both required [47]; and filtration itself delivers substantial modelled risk reduction within a barrier train [32].

#### 7.5. Synthesis: a barrier requirement, stated by scenario

Three independent evidence streams converge: direct log-reduction measurement, depth-dependent mechanism and risk modelling. Media filtration alone, at realistic bed depths and loadings, does not reliably deliver the microbiological quality required for reuse involving plausible human contact, and in particular does not reliably reduce viral risk. This holds across sand, biochar, activated carbon and lignocellulosic media, is reinforced by the finding that constructed wetlands cannot reliably meet microbiological standards alone [3], and matches the green-wall meta-analysis, which advises a disinfection unit for reuse [4]. The conclusion should not be overstated: optimised vegetated biofilters have met an indoor non-potable standard at a median 3.0 log<sub>10</sub> [41]. But granular beds generally do not, viral performance is largely unmeasured, and indicator results do not warrant inference about viral safety [46]. Disinfection should therefore be specified as a barrier wherever the scenario involves human contact: chlorination proved essential in the biochar-sand system [17], and electrochemical disinfection of green-wall effluent achieved more than 3.5 log<sub>10</sub> inactivation at 0.63 to 0.83 kWh m<sup>-3</sup> [44]. Filtration's function within the train is to deliver the organic, solids and turbidity reduction on which disinfection efficacy depends.

### 8. Surfactants and micropollutants

Surfactants distinguish greywater from other low-strength wastewaters: they form a substantial share of the organic load and can inhibit anaerobic biodegradation [6], with influent concentrations of 6 to 7 mg L<sup>-1</sup> LAS measured in mixed household greywater [2]. Removal is strongly process-dependent, and the adsorptive-biological contrast is the clearest argument for a carbonaceous stage. The activated carbon-biochar comparison reached about 0.05 mg L<sup>-1</sup> residual surfactant and about 10 mg L<sup>-1</sup> COD, meeting Italian and Australian standards, with activated carbon superior for anionic and biochar for non-ionic surfactants [11], and the membrane-coupled multi-layer filter reached 99.97% LAS removal with mean effluent surfactant of 0.04 mg L<sup>-1</sup> [37]. For pharmaceuticals and personal care products, sand alone achieves variable removal dominated by biodegradation, and combining GAC with sand in serial, dual or sandwich configurations produces significant enhancement [8], demonstrated by the sandwich filter's 98.2% removal against both single-medium controls [28]; in greywater, a charcoal-based green-wall medium removed 99% of caffeine and 81.2% of DEET while soil and coir media performed better for acetaminophen [12]. Two constraints qualify these results. Adsorptive removal is time-limited by finite capacity, and the long-term studies needed to quantify that limit do not exist for greywater filters (Section 6.4). And consumer product choice strongly influences the micropollutant load but correlates with nothing designers can rely on, so treatment must be robust to the variation rather than depending on source control [1].

## 9. Reuse readiness: benchmarks and the receiving environment

### 9.1. Reuse requirements are scenario-specific and jurisdictional

Terms such as “unrestricted reuse”, “irrigation” and “toilet flushing” carry no universal water-quality requirements: targets vary by jurisdiction, contact scenario, treatment class and monitoring basis, and are expressed variously as indicator concentrations, log-reduction credits or health-based risk. A critical review of 70 agricultural water reuse instruments found them predominantly health-centred, insufficient on emerging constituents and mutually discrepant [48]. Table 5 sets out the primary instruments relevant here, with three cautions. Regulation (EU) 2020/741 applies to reclaimed urban wastewater for agricultural irrigation; it does not automatically extend to household greywater or toilet flushing, so citing it as a greywater standard is a scope error. The United States Environmental Protection Agency guidelines for water reuse are non-binding, with requirements set state by state. And NSF/ANSI 350 certifies an onsite treatment system rather than regulating a water sample. A methodological caution also applies: the numeric limits in these instruments could not be verified against the official texts within the resources of this review, so Table 5 states each instrument’s scope and target type and reports numbers only where a study in the corpus applied a specific threshold; the limits themselves must be checked against the current official text before design or compliance use (Section 13).

**Table 5. Primary instruments relevant to greywater reuse. Legislation and standards are identified by their official designations; numeric values appear only where a corpus study applied and reported a threshold, and instrument limits must be verified against the current official text.**

| Instrument                                                                      | Scope                                                            | Type of target                                                                         | As applied in the corpus                                                                             |
|---------------------------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater, 2006 [49] | Wastewater, excreta and greywater in agriculture and aquaculture | Health-based targets as tolerable disease burden, with pathogen-reduction requirements | $10^{-6}$ DALY per person per year applied in [20]; unrestricted-reuse thresholds applied in [18,17] |
| Regulation (EU) 2020/741 on minimum requirements for water reuse                | Reclaimed urban wastewater for agricultural irrigation only      | Concentration-based quality classes by crop and irrigation method                      | Not applied numerically by any corpus study                                                          |
| US EPA Guidelines for Water Reuse, EPA/600/R-12/618 (2012)                      | Non-binding federal guidance; state-level requirements           | Guidance values by reuse category                                                      | $10^{-4}$ annual infection risk applied in [20,46]; criteria applied alongside WHO in [17]           |
| NSF/ANSI 350, Onsite Residential and Commercial Water Reuse Treatment Systems   | Certification of onsite reuse treatment systems                  | Performance-based system certification                                                 | Not applied by any corpus study                                                                      |
| Australian Guidelines for Water Recycling, Phase 1 (NRMMC, EPHC and AHMC, 2006) | Risk-based national guidance including greywater                 | Risk-based, with indicator targets by end use                                          | Indoor non-potable standard applied in [41]; below 10 MPN per 100 mL applied in [44]                 |

### 9.2. Concentration compliance and risk assessment are distinct

A concentration comparison establishes whether effluent meets a limit at the sampling point; a risk assessment estimates the disease burden following a defined exposure, and depends on the pathogens modelled, dose-response assumptions, exposure frequency and benchmark. The risk studies in this corpus differ on all these axes, from *Salmonella* and rotavirus during maintenance and onion consumption [25], through Monte Carlo simulation of toilet flushing and food-crop irrigation [20] and derivation of permissible influent concentrations for three bacterial pathogens [47], to rotavirus, *Campylobacter* and *Cryptosporidium* during flushing and irrigation [46]. Their conclusions are complementary rather than comparable, and the consistent signal across them is not a numeric threshold but the persistence of viral risk after filtration alone.

### 9.3. The receiving environment is the neglected half of the problem

Treatment performance and reuse safety are distinct, and the receiving compartments are studied less than the filters. Sustained field evidence is unforgiving: comparison of greywater-irrigated residential lots with non-irrigated controls found arsenic, boron, chromium and copper exceeding soil guidelines within four years, with further exceedances in groundwater and surface water [50]. Two treatment-side observations complete the picture: measured sodium adsorption ratio can be as low as 0.6, so sodicity risk is site- and detergent-specific [2]; and treatment can worsen the parameters governing irrigation suitability, as when volcanic tuff outperformed gravel on organics while raising effluent salinity and sodium indices [31]. A filter cannot be evaluated apart from the irrigation regime, soil and detergent chemistry that determine whether reuse is sustainable.

### 9.4. Fit-for-purpose conclusions by scenario

The defensible position is a barrier framework matching barriers to exposure pathway rather than to technology (Figure 4). Sub-surface irrigation of non-food or cooked crops carries the lowest exposure: source control, pre-treatment and filtration suffice, with multi-season monitoring of soil conductivity, sodium indices and metals [50,31]. Irrigation of produce eaten raw requires disinfection in addition, given persistent modelled rotavirus risk [25,46] and the bathroom-laundry versus kitchen distinction [20]. Toilet flushing and any aerosol- or contact-generating use require disinfection and, where achievable, a residual, since neither granular beds nor wetlands reliably meet microbiological standards alone [3,44,18]. Maintenance exposure, the dominant pathway in the one assessment that modelled it [25], requires procedural controls and user guidance rather than additional treatment, and is almost absent from the design literature.

## 10. Comparative positioning

Media filtration is best positioned by what each technology does well. Constructed wetlands remove bulk parameters strongly but cannot reliably meet microbiological standards alone [3]; green walls achieve high organic removal with performance that scales with areal mass load, and likewise require a disinfection unit for reuse [4]; and biochar-based columns span the full range of reported performance from 50 to 99% removal, with long-term assessment still outstanding [10]. Media filtration occupies the low-energy, low-skill end of this spectrum, with correspondingly lower and more variable performance for dissolved and microbiological fractions. Its capital and energy advantages are genuine, but no study in the corpus reports cost per cubic metre actually reused at a defined effluent class including media replacement and disinfection, so life-cycle viability at household scale remains an open matter rather than an established advantage.

## 11. Critical analysis of the evidence base

### 11.1. Domain-level findings, with stated denominators

Each of the 73 primary studies was scored on five domains as adequate, inadequate or unclear (Table 6; study-level matrix in Supplementary File S4; codebook in S5), with unclear treated as missing information and excluded from that domain's denominator. Control adequacy was assessable for all 73: 59 studies include an internal comparator and 14 do not, but, as Section 5 establishes, none of the 59 comparators is of the type that identifies a layering benefit. Replication and variance was assessable for only 19 studies, all of which report dispersion or replicates; the record is silent for the other 54, and no inference is drawn about their conduct. Matrix realism was assessable for 63: 45 used real greywater or a real fraction, 18 synthetic or proxy matrices. Duration adequacy was assessable for 26, of which 8 were adequate and 18 inadequate, with 47 unclear; it follows that no statement about the typical study duration in this literature is supportable, and an earlier claim that the modal duration was of the order of weeks is withdrawn. Loading completeness was assessable for 39, of which 28 report hydraulic loading with correct dimensions; organic loading is reported far less often. The large unclear counts are themselves a principal finding: a full-text appraisal would be required before the domain scores could be read as characterising the studies rather than their accessible records.

**Table 6. Appraisal of the 73 primary studies. "Unclear" means the accessible record does not report the domain and is excluded from the denominator; it is not interpreted as inadequate conduct.**

| Domain                   | Adequate | Inadequate | Unclear | Assessable n | Principal implication                                                          |
|--------------------------|----------|------------|---------|--------------|--------------------------------------------------------------------------------|
| Control adequacy         | 59       | 14         | 0       | 73           | Comparators are common; none identifies a layering benefit                     |
| Replication and variance | 19       | 0          | 54      | 19           | Undeterminable for most of the corpus from the accessible record               |
| Matrix realism           | 45       | 18         | 10      | 63           | Most studies use real greywater; the best-controlled comparisons often do not  |
| Duration adequacy        | 8        | 18         | 47      | 26           | No statement about typical duration is supportable; service life unestablished |
| Loading completeness     | 28       | 11         | 34      | 39           | Cross-study loading comparison obstructed for half the corpus                  |

### 11.2. Consequences for the strength of specific claims

Well supported: carbonaceous media outperform sand for dissolved organic carbon and surfactants; adsorption and biodegradation both contribute materially in carbon filters, in proportions set by influent and history; microbial removal by granular beds on real greywater is generally insufficient for contact reuse; microbial removal declines as loading rises; greywater composition is highly variable and source-dependent; and some organic media leach dissolved organic carbon. Conditionally supported: an added adsorptive stage improves dissolved-fraction removal (CT2 designs only, depth not equalised [18,35,28,36]); pyrolysis rather than botanical origin explains lignocellulosic performance (one controlled comparison [29]); organic removal is loading-insensitive (holds only in generously sized beds [24,37]); and maturation improves performance (duration undetermined for greywater [43]). Provisional, single-study: physically mixing media degrades most endpoints [34]. Not currently supported: that layered configurations outperform their constituents at equal size, for which no identifying comparison exists; that performance rises with layer number; that these filters sustain multi-year service under raw-greywater loading; that filtration alone meets unrestricted-reuse requirements; and that any general ranking of media can be constructed, since superiority reverses between anionic and non-ionic surfactants [11], between bacterial and viral endpoints under rising organic load [45], and between treatment and irrigation-suitability indices [31].

### 11.3. Alignment between evidence and application context

The technology examined here is advocated principally for low- and middle-income settings, and within this corpus studies from such settings are well represented and supply several of the most relevant Tier A comparisons [2,29,35,18,31,32]. They are, however, on average shorter and less likely to report variance than the European studies that supply most of the analogue comparisons, a structural feature of research funding rather than a criticism of individual authors, and one that constrains transfer of findings between contexts.

## 12. Future scope: a prioritised research agenda

### 12.1. First priority: the depth-matched factorial experiment

The field's central claim is unidentified because no study holds depth and contact time constant while varying configuration. The required experiment is specific and feasible: columns of identical total depth, media mass and empty-bed contact time fed a common real greywater at matched loading, comparing a homogeneous bed of each constituent, the layered configuration and a physically mixed configuration of the same composition, replicated, with variance reported and a run length beyond maturation. A factorial arrangement of media identity against depth would separate the configuration effect from the depth effect confounding every reported comparison. Until then, guidance on layer number and sequence is engineering convention, not evidence-based design.

### 12.2. First priority: service life as a transferable endpoint

No study determines adsorptive exhaustion for any medium receiving raw greywater at household loading (Section 6.4). What is needed is not merely longer experiments but a different endpoint: breakthrough curves, cumulative bed volumes and contaminant mass per unit medium, head-loss thresholds and explicit replacement criteria, distinguishing exhaustion from clogging and biological stabilisation, reported as a service interval in months at a stated loading [11,15,27].

### 12.3. First priority: viral endpoints and indicator validity

*Escherichia coli* is not an appropriate indicator for greywater reuse risk [46], viral removal is consistently lower than bacterial removal in the same material [42], and media rankings differ by organism class [45]. Bacteriophage and multi-surrogate panels are demonstrably feasible [39,27] and should become routine, with protozoan surrogates wherever produce eaten raw is irrigated.

### 12.4. Second priority: standardised mass-flux reporting

A minimum reporting set should comprise influent and effluent concentrations with dispersion and replication; hydraulic and organic loading with correct dimensions; contact time; bed depth, media mass and grain size; cumulative bed volumes; observation period; and whether disinfection preceded the reported sample, with areal mass removal reported alongside percentages. That structured data enable synthesis is demonstrated by the green-wall meta-analysis [4]; the same is achievable for granular beds.

### 12.5. Second priority: replicate the mixing result in real greywater

The finding that mixing degrades most endpoints rests on one synthetic-matrix study [34] with no Tier A or B test (Table 3). Because mixing is operationally simpler than layering, the mixed-versus-layered-versus-homogeneous arms of the Section 12.1 factorial would resolve both uncertainties in one experiment.

### 12.6. Second priority: leaching and conditioning of organic media

Dissolved organic carbon release from organic media is documented by three independent groups [7,30,12] but is neither systematically quantified nor addressed by a conditioning protocol. Column leaching kinetics and pre-conditioning treatments should be characterised against early effluent quality, the period in which users judge whether a system works.

### 12.7. Third priority: field validation under real operation

Maintenance is the dominant exposure pathway in the one assessment that modelled it [25], yet user behaviour, cleaning practice and failure modes are almost undocumented, and the reassuring operational evidence on intermittency comes from a single system [38]. Longitudinal field study of installed units, monitoring effluent quality and user practice together, is required.

### 12.8. Third priority: receiving-environment monitoring

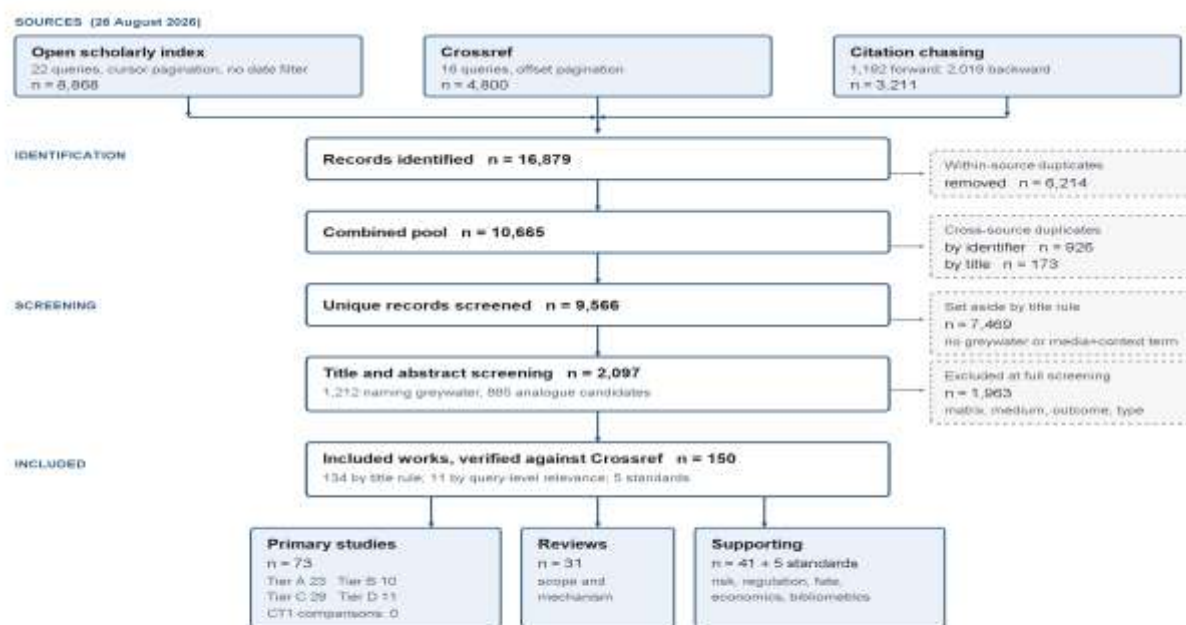
Soil, groundwater and surface-water effects of sustained greywater irrigation are documented at few sites [50]. Multi-year monitoring with treatment level as an explicit variable would quantify the marginal environmental benefit of filtration, which no study currently does.

## 13. Limitations of this review

The search is documented and archivable but not exhaustive: work matching no query string and outside the citation neighbourhood of included studies is missed, and practitioner and grey literature, which hold much operational experience with household filters, are largely absent; the corpus is weighted toward indexed, English-language publication. Screening, extraction and appraisal were performed by a single analyst, so screening error cannot be quantified and no inter-rater statistic is reported; this is a principal reason the review does not claim systematic-review status and reports counts as corpus properties. Seventeen primary studies were appraised from bibliographic record and abstract only; no quantitative result is attributed to them, and the six whose full texts would most change the synthesis, the bark-charcoal-sand series and the operating-mode, long-term sand-filter and biofilter-media studies identified in Supplementary File S4, are the most valuable next reading. More broadly, the large unclear counts in Table 6 mean the appraisal characterises accessible records, not study conduct. No pooled effect estimates are provided, for the reasons in Section 2.8; comparative statements rest on consistency of direction across independent studies. The reference list is limited to the works discussed directly, in accordance with the journal's limit, so many corpus studies appear only in Supplementary Files S1 and S4. Finally, the numeric limits of the reuse instruments in Table 5 could not be verified against official texts and must be checked before use, and transfers from the drinking-water and wetland literatures are made for mechanism only, labelled with their tier at each point of use.

## 14. Conclusions

This review set out to test, rather than restate, the design proposition underlying much of the on-site greywater filtration literature, and four conclusions follow. First, the central claim is unidentified rather than refuted: across 73 primary studies, none compares a layered configuration with its constituents at matched depth, media mass and contact time, so the effect attributable to layering has never been separated from the added depth and residence time that accompany it in every reported design. What the controlled evidence supports is narrower and worth stating exactly: adding adsorptive capacity to a bed that lacks it improves removal of the dissolved fraction, and substituting pyrogenic or activated carbon for sand improves organic and, modestly, microbial removal. Neither is a layering benefit, and in the single test of physical mixing, most endpoints deteriorated. Second, loading sensitivity is endpoint-specific: organic removal is robust in beds generously sized for their organic flux and declines in overloaded ones, while microbial removal declines consistently as loading rises, so a design optimised on organic criteria is under-designed for pathogens. Third, microbiology is the binding constraint, and the conclusion holds by system class: granular beds on real greywater span roughly 0 to 2.9 log<sub>10</sub> for faecal indicators, optimised vegetated biofilters reach a median of about 3 log<sub>10</sub>, viral performance is largely unmeasured and cannot be inferred from indicators, and residual viral risk persists after filtration alone. Terminal disinfection is therefore a design requirement for any scenario involving plausible human contact, with filtration supplying the low-turbidity feed on which disinfection depends. Fourth, the evidence base is not yet adequate to the confidence with which these systems are presented: comparators are common but none is identifying, replication and duration are undeterminable for most of the corpus, and several of the best-controlled comparisons used proxy matrices. None of this means the technology fails; the consistency of direction across independent groups indicates that it works, within limits this review has tried to state exactly. It does mean that current quantitative design guidance rests on weaker foundations than its presentation suggests, and that the priorities of Section 12, a depth-matched factorial comparison, service life as a transferable endpoint, viral endpoints and mass-flux reporting, are the conditions for turning a widely deployed and promising technology into an engineered one.



Reference list of this article: 50 works discussed directly in the text, each with a digital object identifier. All 150 included works, with identifiers, are listed in Supplementary Files S1 and S4.

Seventeen primary studies were appraised from bibliographic record and abstract only; no quantitative result is attributed to them. Screening, extraction and appraisal were performed by a single analyst; counts describe the assembled corpus, not the field.

**Figure 1. Flow of records through identification, deduplication, screening and inclusion.**

Three discovery routes were used on 26 August 2026: 22 paginated queries of an open scholarly index with no relevance ceiling or date filter, 16 paginated Crossref queries, and backward and forward citation chasing of every included primary study. Deduplication was applied within each source, then across sources by digital object identifier, then by normalised title. Title screening applied a documented

keyword rule and full screening applied the eligibility criteria of Section 2.3. All included works were verified against the Crossref registration record; the reference list of this article is limited to the works discussed directly, and the complete set of included works is given in Supplementary Files S1 and S4.

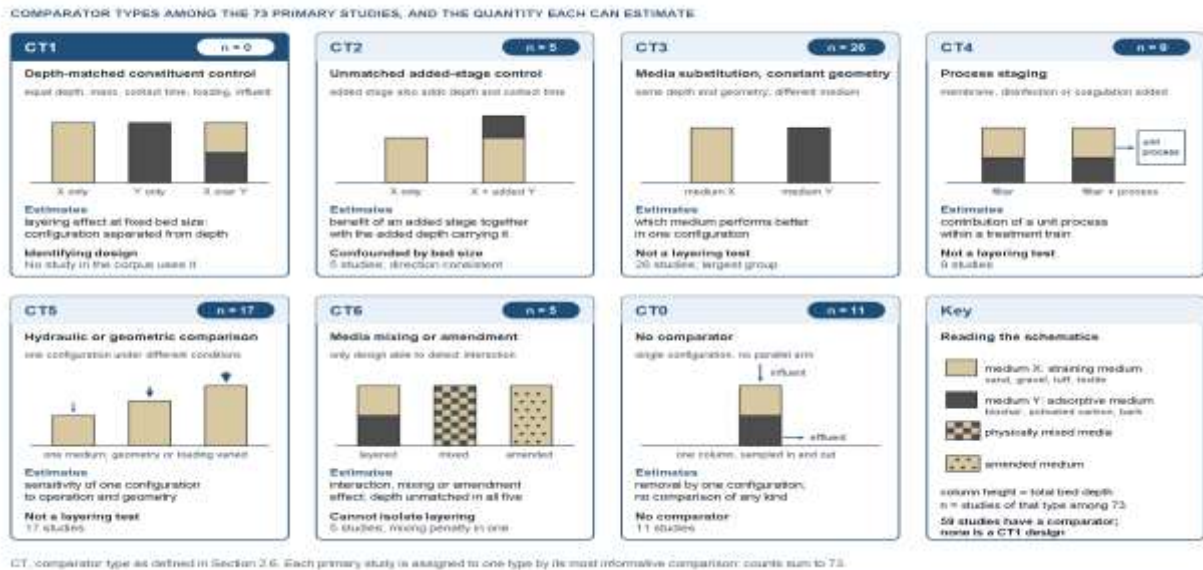


**Figure 2. Comparator designs and the causal quantity each can estimate, with the number of studies of each type among the 73 primary studies.**

Schematic columns show the arms compared: shading denotes different media and height denotes total bed depth. Only a CT1 design, in which every arm has identical total depth, media mass, contact time, loading and influent, can attribute an effect to layering rather than to bed size, and no study in the corpus uses it. Fifty-nine studies include an internal comparator, but each estimates a quantity other than the layering benefit that the design literature asserts.

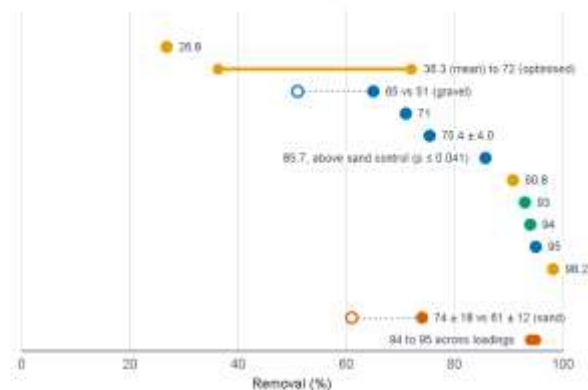
### A Removal of organic matter (COD or BOD)

Greywater, real or synthetic

- C Spychala et al. 2019 - medium sand columns, artificial greywater - COD
- C Nazif et al. 2023 - sand and activated carbon, 49 configurations, synthetic - COD
- A Albalawneh et al. 2017 - volcanic tuff vs gravel, household field - COD
- A Taylor et al. 2023 - pyrolysed coconut husk, bench - COD
- A Hassan et al. 2024 - geotextile with cotton, household - total COD
- A Appiah-Effah et al. 2026 - sand + 85 mm GAC vs sand, school handwashing - COD
- C Akbari et al. 2025 - coagulation + three-layer sand and carbon - COD
- B Dalahmeh et al. 2016 - biochar filter, field - BOD<sub>5</sub>
- B Sharaf et al. 2020 - GAC biofilter, 253 days - total COD
- A Shaikh and Ahammed 2023 - fine sand at 320 L m<sup>-2</sup> d<sup>-1</sup> - COD
- C Babaei et al. 2019 - multilayer slow sand + MF/UF - COD

External analogues, Tier D

- D Kaetzel et al. 2020 - biochar vs sand, settled sewage - COD
- D Perez-Mercado et al. 2018 - biochar, on-site wastewater - COD



### B Microbial reduction

Packed granular beds, real greywater

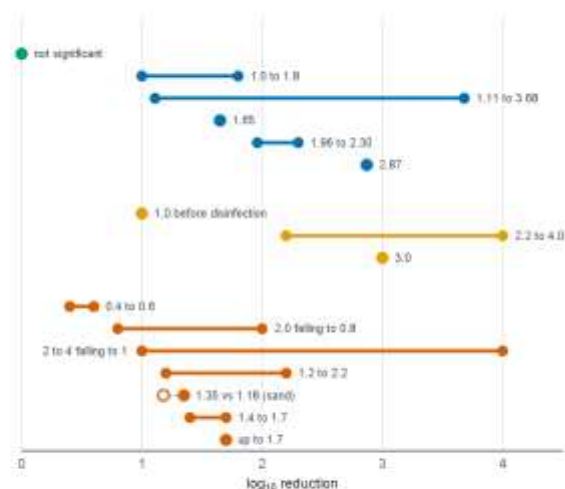
- B Dalahmeh et al. 2016 - biochar, field - *E. coli*
- A Appiah-Effah et al. 2026 - sand + GAC - *Salmonella* to total coliforms
- A Mortula et al. 2023 - sand filtration - faecal coliforms
- A Shaikh and Ahammed 2023 - fine sand - faecal coliforms
- A Mortula et al. 2023 - blast-furnace slag - faecal coliforms
- A Taylor et al. 2023 - pyrolysed coconut husk - faecal coliforms

Vegetated biofilters

- C Bakheet et al. 2020 - green wall, real greywater - *E. coli*, total coliforms
- C Sami et al. 2023 - green wall, biochar substrate, real greywater - *E. coli*, enterococci
- C Jung et al. 2019 - 80 biofilter columns, synthetic greywater - *E. coli*, median

External analogues, Tier D

- D Trikanand et al. 2023 - slow sand filter material - bacteriophage PhiX174
- D Perez-Mercado et al. 2019 - biochar columns, rising loading - viruses
- D Perez-Mercado et al. 2019 - biochar columns, rising loading - bacteria
- D Duran Romero et al. 2020 - biosand filter - *E. coli*
- D Kaetzel et al. 2020 - biochar vs sand, settled sewage - *E. coli*
- D Trikanand et al. 2023 - slow sand filter material - *E. coli*
- D Kaetzel et al. 2018 - biochar anaerobic filter, raw sewage - faecal indicators



A B C D Evidence tier A to D (Table 2)

● value reported by the study

— range reported by the source

○ paired control in the same study

Values are not commensurable between studies: influent strength, loading, bed depth and matrix differ, and no pooled estimate is implied. Hassan et al. 2024 is omitted from panel B because the record does not separate filtration from the subsequent disinfection step.

**Figure 3. Reported performance by endpoint for the studies discussed in the text, with evidence tier.**

Panel A, removal of organic matter; panel B, microbial reduction on a logarithmic scale, arranged so that packed granular beds treating real greywater can be compared with vegetated biofilters and external analogues. Each marker is a value reported by the cited study; horizontal bars show ranges reported by the source, and open markers denote a paired control within the same study. Values are not commensurable between studies because influent strength, loading, bed depth and matrix differ, so the panels display the evidence with attribution rather than a ranking of media, and no pooled estimate is implied.

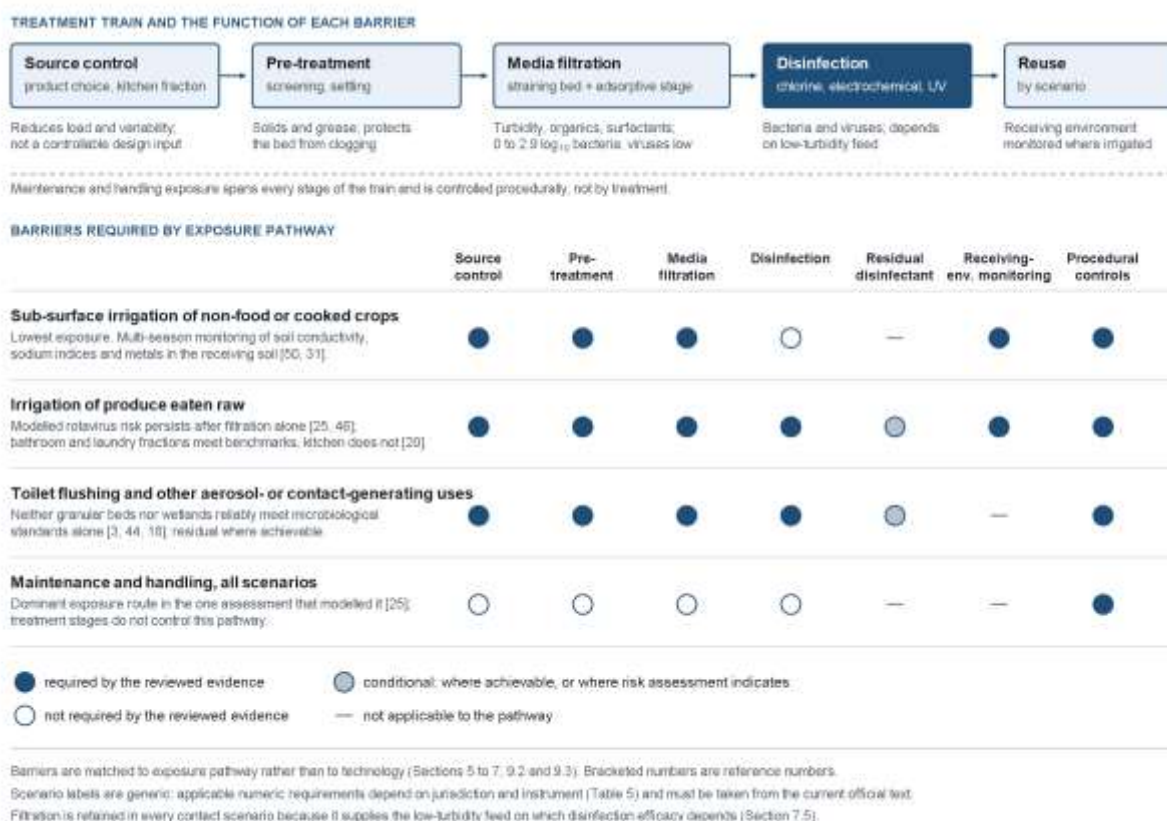


**Figure 4. Barrier framework for reuse readiness. The upper strip shows the treatment train;**

the matrix below matches barriers to exposure pathway rather than to technology, drawing on the treatment evidence of Sections 5 to 7, the risk assessments of Section 9.2 and the environmental-fate evidence of Section 9.3. Maintenance exposure appears as a distinct pathway requiring procedural rather than technological control. Scenario labels are generic: applicable numeric requirements depend on jurisdiction and instrument and must be taken from the current official text.

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