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Ankita Pokhrel

College of Environmental Science and Engineering, Tongji University; Key Laboratory of Water Supply, Water Saving and Ecological Governance in the Yangtze River Delta, Ministry of Water Resources, Shanghai 200092, China

Bernard Lassimo Diawara

College of Environmental Science and Engineering, Tongji University; Key Laboratory of Water Supply, Water Saving and Ecological Governance in the Yangtze River Delta, Ministry of Water Resources, Shanghai 200092, China

Mohamed Yateh

College of Environmental Science and Engineering, Tongji University; Key Laboratory of Water Supply, Water Saving and Ecological Governance in the Yangtze River Delta, Ministry of Water Resources, Shanghai 200092, China

Xianwei Zeng

Zhejiang Anji Water Co., Ltd., Anji, Huzhou 313300, Zhejiang, China

Yulin Tang

tangtongji@126.com

College of Environmental Science and Engineering, Tongji University; Key Laboratory of Water Supply, Water Saving and Ecological Governance in the Yangtze River Delta, Ministry of Water Resources, Shanghai 200092

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Life cycle assessment of drinking water treatment plants: a plant-level critical review of evidence usability and grid dependence

Ankita Pokhrel[1], Bernard Lassimo Diawara[1], Mohamed Yateh [1], Xianwei Zeng[2], Yulin Tang[1]*

[1] College of Environmental Science and Engineering, Tongji University; Key Laboratory of Water Supply, Water Saving and Ecological Governance in the Yangtze River Delta, Ministry of Water Resources, Shanghai 200092, China
[2] Zhejiang Anji Water Co., Ltd., Anji, Huzhou 313300, Zhejiang, China

*Corresponding author: Yulin Tang. Email: tangtongji@126.com;

Telephone: +86-21-65982708

Abstract

Life cycle assessments (LCAs) of drinking water treatment plants (DWTPs) are now common, but reviews that count publications hide variation within papers and treat repeated assessments of one plant as independent. We re-extracted 37 LCA publications at the level of individual plants and scenarios, giving 112 cases. These describe 51 physical systems but only 30 independent assessments, because nine publications re-analyze two plants. A global warming potential (GWP) can be recovered for 55% of cases and a specific electricity consumption for 64%; no other midpoint category exceeds 27%. Only three publications state the carbon intensity of the electricity they modeled, so most footprints cannot be split between plant design and electricity supply. Seven within-study comparisons, which hold the system fixed and change only the electricity supply or the treatment train, show that grid leverage depends on the train. It is large for electricity-driven processes such as membranes, pumping and ultraviolet (UV) disinfection, and small where the burden lies in chemicals and activated carbon. Process, hydraulic and supply-chain choices also change footprints substantially. For non-climate impacts, the limited evidence points to chemical and material supply chains. We propose a nine-parameter minimum reporting set to make future studies comparable.

Keywords

Life cycle assessment; Drinking water treatment; Global warming potential; Energy intensity; Grid carbon intensity; Environmental reporting

1 Introduction

Drinking water treatment is energy intensive, and because treated water is produced in very large volumes, small differences in the electricity or chemicals used per cubic meter add up to substantial burdens (Duarte et al. 2026). Life cycle assessment (LCA) has become a standard tool for quantifying them. Published LCAs of full-scale drinking water treatment plants (DWTPs) have grown steadily since 2010 and cover conventional, ozone and granular activated carbon (GAC), membrane, advanced oxidation, disinfection, contaminant-specific and decentralized options in several regions (Bensitel et al. 2026; Garfí et al. 2016; Wang et al. 2019). Reviews of LCA in the water sector are mostly narrative and count publications (Gallego-Schmid and Tarpani 2019; Ogbu et al. 2025): they list the impact categories assessed, the dominant life-cycle stage and the qualitative conclusions. For drinking water this hides several properties of the literature that matter to anyone who wants to reuse its numbers.

Papers often report several plants or scenarios, and several papers may describe the same plant, so counting publications loses within-paper variation and counts some plants more than once. Plant-level re-extraction has been applied to wastewater treatment (Li et al. 2021) but, to our knowledge, not to drinking water. Much of this literature also does not report numbers that a later reader can use: results appear as unlabeled bar charts, as endpoint scores, or as differences from a baseline whose absolute value is not given. The usable share of these results has not been

quantified, so counting how often a category is assessed can overstate what is known about it (Corominas et al. 2013). Finally, studies showing strong grid sensitivity and sector-scale analyses have encouraged the view that a DWTP's carbon footprint is governed mainly by the carbon intensity of its electricity (Bonton et al. 2012; Ramazan et al. 2026; Roth et al. 2022; Zib et al. 2021). Testing that view requires both the electricity a plant uses and the carbon intensity of that electricity, and the second is rarely reported.

This review had four aims: (i) to re-extract the DWTP LCA literature at plant level, recording the source of every value, and describe its redundancy, gaps and methods; (ii) to quantify how much of the reported evidence is numerically usable, and why the rest is not; (iii) to summarize what the literature shows about the contributions of electricity, chemicals and infrastructure, relying on within-study comparisons where possible; and (iv) to propose a minimum reporting set for future studies.

2 Methods

This is a structured critical narrative review. It describes results at plant level and does not pool effect sizes across studies, for three reasons.

First, reported intensities are not directly comparable: functional units range from 1 m^3 at the plant gate to 1 m^3 at the household tap, boundaries differ, and some functional units are missing or contradictory. Second, the carbon intensity of the modeled electricity is rarely reported. It can sometimes be back-calculated from a study's own greenhouse-gas result and electricity use, but such a value is a rearrangement of the footprint it would explain and cannot serve as an independent predictor. Third, the observations are not independent: the 112 cases come from 37 publications, 30 independent assessments and 51 physical systems, and one plant contributes 15 cases. We therefore also report how the main statistics change when each system is counted once (Online Resource 1, Table S9). We describe distributions within strata, report the provenance of every number, and address the grid question with studies that hold one system and inventory fixed while varying only the electricity supply or the treatment train.

2.1 Search strategy

Web of Science, Scopus, ScienceDirect and Google Scholar were searched for peer-reviewed LCA studies of full-scale DWTPs published between 2000 and 2025. The search strings, the database-specific filters and the full inclusion and exclusion criteria are given in Online Resource 1 (Tables S1 and S2). Two reviewers screened titles, abstracts and full texts independently, and disagreements were resolved by discussion.

The search identified 839 records, of which 148 were duplicates. Of the 691 unique records, 533 were excluded at title and abstract. Of the 158 reports sought for retrieval, four could not be obtained and 154 were assessed in full text. Of these, 117 were excluded: 75 were not LCAs of drinking water treatment on full-text reading, 16 assessed the entire water-supply system beyond the DWTP boundary, 9 had partial technology scope or reported greenhouse gases only, 8 had methodological problems or presented no LCA-based result, 6 addressed pilot-scale or planned plants, and 3 were special or remote-case designs. Thirty-seven studies met all criteria. The screening record is presented as a PRISMA 2020 flow diagram (Page et al. 2021) in Online Resource 1 (Fig. S1). The review is not registered as a systematic review. The earliest eligible study dates from 2010, so the effective coverage is 2010 to 2025. Studies published in 2026, after the search closed, are cited for context only and are not part of the corpus.

2.2 Data extraction and eligibility

Each publication was read in full, including inventory tables, figure data labels and supplementary material, and re-extracted at the level of the individual plant or clearly defined treatment scenario. The extraction schema is given in Online Resource 1, Table S3, and the full dataset in Online Resource 2.

Every numeric cell carries one of five provenance tags. Reported values are printed in the source publication, and derived values are computed from printed values. Carried values were printed for another case, or in a companion publication on the same system, and apply unchanged. Assumed values (electricity carbon intensity only, five cases in two publications) can be neither found nor derived from the source; they are counted in Table 2 but excluded from all statistics. Not reported means that no usable value exists. Annual plant totals were divided by the production volume given in the same paper. Identity was recorded at three levels. A case is a plant configuration or a defined scenario of it. A physical system is one plant or supply route, operational or modeled; trains, operating points and electricity supplies modeled for the same site belong to one system, while separate sites and non-network

routes (bottled water, household devices, wells and rainwater harvesting) are separate systems. An independent assessment, or plant group, is one publication or a family of publications reusing one site inventory; the evidence for each grouping is given in Online Resource 1, Table S5.

Three rules govern whether a case enters a summary statistic. First, municipal statistics include only cases whose functional unit maps onto 1 m³ of drinking water supplied by a municipal system, at the plant gate or the tap; bottled water, point-of-use devices and stand-alone disinfection steps are reported separately. Second, a plant described by several publications is counted once. Third, a value is withheld if it is contradicted by the study's own inventory, physically implausible by a wide margin, or tied to a service other than drinking water production. The two cases of de Jesus et al. (2024) passed full-text screening but describe process water for an oil refinery; they remain in the corpus count and the appraisal, and all their values are withheld. Every withheld value and its defect is listed in Online Resource 1, Table S4. No value was withheld for being an outlier.

Implausibility was judged for complete treatment plants against two bounds: a lower bound of 0.01 kWh m^{-3}, roughly the base load of instrumentation, control, dosing and lighting at a plant without pumping, and an upper bound equal to the specific energy of seawater reverse osmosis, about 3 to 4 kWh m^{-3} (the desalination plant in the corpus reports 4.3 kWh m^{-3}). The bounds were not applied to disinfection steps or alternative supply. Two cases were withheld in full; two electricity values were set aside (39.6 kWh m^{-3} at one Taiwanese plant and 0.0026 kWh m^{-3} at one Colombian plant), and ten global warming potential (GWP) values were set aside.

2.3 Reporting-quality appraisal

Each publication was scored from 0 to 2 on six criteria: functional unit, system boundary, currency of the impact assessment method, modeling design, sensitivity or uncertainty analysis, and transparency about the background electricity. The total (0 to 12) is expressed as a percentage of the maximum. The criteria follow reporting requirements of ISO 14044 and the ILCD Handbook. Five criteria are scored from the extraction dataset; only sensitivity analysis needs a separate reading. The instrument and the scores are given in Online Resource 1, Tables S6 and S7.

Existing appraisal tools assess overall study quality, risk of bias or data quality; this instrument asks only whether a later reader can reuse a reported result. Its thresholds are our own and have not been externally validated, and it measures reporting completeness, not the validity of the underlying assessment.

3 Results and Discussion

3.1 Characteristics of the evidence base

Re-extraction yields 112 case studies (Table 1): 61 baseline plant configurations and 51 defined scenarios of them, such as an alternative coagulant, an optimized operating point, a substituted electricity mix or an added unit process. Twelve of the 37 studies appeared in 2023 to 2025 and 22 since 2018 (Fig. 1a). Inventory years span 2007 to 2023, so several much-cited studies model plants as they operated more than fifteen years ago, on electricity datasets that no longer describe their grids.

Table 1 Composition of the plant-level case base (n = 112 cases from 37 publications, 30 independent assessments and 51 physical systems)

Stratum	Level	Cases	% of cases
Region	Europe	40	35.7
	South America	25	22.3
	North America	20	17.9
	East and Southeast Asia	17	15.2
	West Asia	6	5.4
	South Asia	3	2.7
	Africa	1	0.9
Income group	High income	74	66.1
	Upper-middle income	32	28.6
	Lower-middle income	6	5.4
Treatment class	Conventional	38	33.9
	Conventional plus ozone or activated carbon	23	20.5
	Disinfection only	18	16.1

Stratum	Level	Cases	% of cases
	Membrane filtration	12	10.7
	Alternative or decentralized supply	9	8.0
	Biological filtration	7	6.2
	Contaminant-specific removal	3	2.7
	Advanced oxidation	1	0.9
	Desalination	1	0.9
System boundary	Gate-to-gate	56	50.0
	Cradle-to-gate	41	36.6
	Cradle-to-grave	15	13.4
Supply family	Municipal DWTP[a]	84	75.0
	Disinfection only	18	16.1
	Alternative supply[b]	10	8.9
Case type	Baseline plant configuration	61	54.5
	Defined scenario of a baseline	51	45.5

[a] Includes the two withheld refinery process-water cases of de Jesus et al. (2024). [b] Alternative or decentralized supply (9 cases) plus one desalination plant

Twenty-two countries are represented (Fig. 1b), including the Czech Republic (Klimtová et al. 2025), Greece (Baltrocchi et al. 2024), Brazil (Pithon et al. 2022) and the United States (Wang et al. 2019). Europe contributes 36% of cases, South America 22%, North America 18% and East and Southeast Asia 15%. Only one study is from Africa and none from sub-Saharan Africa, Central Asia or Oceania. Sixty-six percent of cases are in high-income countries, 5% in lower-middle-income countries and none in low-income countries, so regions where much new treatment capacity is being built are largely missing from the evidence.

Conventional coagulation-and-filtration trains account for 34% of cases and conventional trains with ozonation or activated carbon for 21%, followed by disinfection only (16%) and membrane filtration (11%). Advanced oxidation, desalination and contaminant-specific removal have one to three cases each, too few to characterize. Gate-to-gate boundaries are the most common (50%), ahead of cradle-to-gate (37%) and cradle-to-grave (13%). Construction is modeled in 16 publications (49 cases) and plant throughput is reported in 25 (69 cases); with 38% of cases lacking throughput, the literature cannot yet show whether plant size affects the footprint.

There are fewer independent assessments than publications. Nine publications, a quarter of the corpus, describe only two plants and contribute 21 cases, so the 37 publications amount to 30 independent assessments. Five analyze one plant with ozonation and GAC on the Seine near Paris (Ahmadi et al. 2016; Ahmadi and Tiruta-Barna 2015; Capitanescu et al. 2016; Mery et al. 2013, 2014). They share a process-model library, a 2007 site inventory and one funding instrument, and the three optimization papers use the same base case, including a coagulant dose of 61 ppm and a GAC regeneration frequency of 375 cycles. Four report one Malaysian plant with one operating inventory (Sharaai et al. 2010, 2011, 2012a, 2012b); the later three add a construction stage and each applies a different impact assessment method. Neither family mentions the reuse in its abstract, so counting publications would overstate how often European and Southeast Asian DWTPs have been studied by a factor of four to five. Conversely, some publications describe several systems, for example four Colombian plants (Rodriguez et al. 2016), four Indonesian and Taiwanese plants (Ouattara et al. 2024) and five Taiwanese plants (Shiu et al. 2023). Online Resource 2 gives the system assigned to every case.

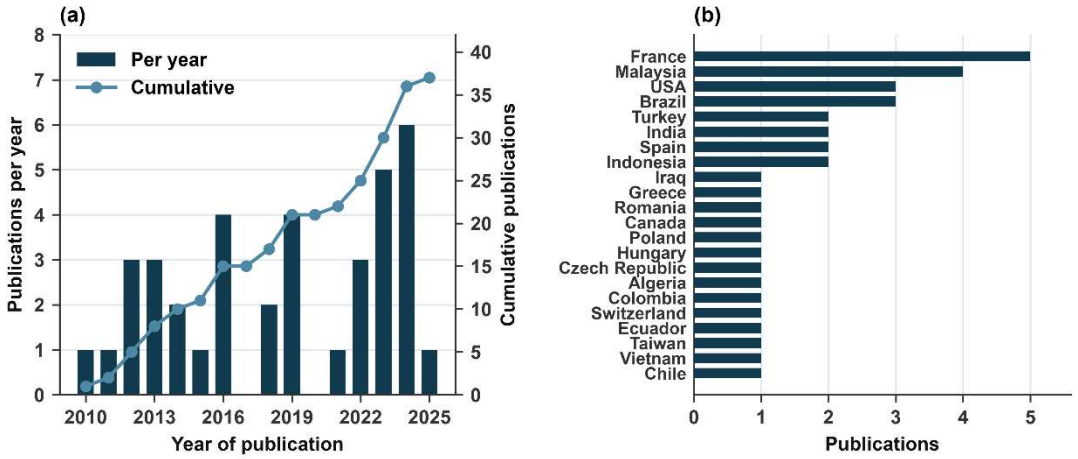


Fig. 1 *Publication activity and geographic distribution of the studies, 2010 to 2025. (a) Publications per year. (b) Publications by country of the plant assessed.*

3.2 Methodological practices

Ninety-one of the 112 cases declare a volumetric functional unit of 1 m³ (or 1,000 m³), usually of treated water and sometimes of water delivered to the user, a distinction rarely flagged although it changes the result by the whole of distribution pumping. Thirteen cases in nine publications carry a defective functional unit: no functional unit is quantified (Karnaningroem and Anggraeni 2021); one liter is declared but results are printed per cubic meter (Mohamed-Zine et al. 2013); 1 m³ for 1 year at 0.03 m³ s⁻¹ is declared without explaining the normalization (Salazar et al. 2022); the unit treatment processes are called functional units (Sarraf and Deswal 2023); one kilogram of disinfected water is used (Nitkiewicz and Jachimowski 2019); the daily clean-water production rate is used (Wang et al. 2019); and 1 m³ per day is declared against an inventory consistent only with 1,000 m³ (Sharaai et al. 2011, 2012a, 2012b). Two more publications use a non-volumetric service: annual arsenic removal (Jones et al. 2013) or a milligram of arsenic removed alongside a cubic meter (Baltrocchi et al. 2024). The functional unit is one of the two highest-scoring criteria in the appraisal (mean 1.68 of 2), so these defects look like transcription errors rather than misunderstanding. For most of them a per-cubic-meter value could be reconstructed from annual totals or the inventory (Online Resource 1, Table S4), but only by assumptions a reader should not have to make; for two publications no convertible value could be recovered.

Boundary labels do not behave as their nesting implies. Among municipal cases, gate-to-gate cases have a higher median GWP (0.24 kg CO_2-eq m^{-3}, n = 25) than cradle-to-gate cases (0.16, n = 14), although gate-to-gate is nominally the narrower boundary; cradle-to-grave cases are highest (0.47, n = 7) (Fig. 2d). The inversion reflects study composition and labeling. Fourteen of the 25 gate-to-gate values come from the Seine plant, whose inventory includes the production of activated carbon and chemicals despite its label, and three are CO_2-only values from the Malaysian plant; the cradle-to-grave stratum is six scenarios from one Canadian study and one Brazilian case. Boundary labels therefore cannot be used to adjust between studies. Infrastructure is the most affected component and the least reported: construction is modeled in 16 publications and its contribution share is reported numerically in three. Where modeled, its share can be large: 24 to 45% of the aggregated impact of the low-pressure reverse osmosis train in Roth et al. (2022), up to 27% from filter-housing steel in (Jones et al. 2018b), and up to 80% of the infrastructure impacts of the chlorine contact zone from steel baffles in Jones et al. (2018a).

The corpus uses twelve method families, most commonly ReCiPe (12 publications), CML (8, plus one unnamed method identifiable as CML-IA), Eco-indicator 99 (4), IMPACT 2002+ (3) and TRACI (3), often without a version or, for ReCiPe, a cultural perspective. Ecoinvent is named by 28 publications in at least seven versions (2.2 to 3.9.1); SimaPro is used in 23, Umberto in five, GaBi or LCA for Experts in three and openLCA in one. For GWP100 the methods share an IPCC basis, although factors differ between IPCC reports and in the treatment of biogenic carbon. Toxicity, ecotoxicity and resource models differ much more, so we harmonized category labels only, never characterization factors, and report non-climate results as directions of effect.

Five publications reach high confidence (at least 75% of the maximum score), 17 moderate (50 to 74%) and 15 low (below 50%); the median is 50% (interquartile range 33 to 67%). Criterion means (out of 2) are 1.70 for impact

assessment method, 1.68 for functional unit, 0.89 for modeling design, 0.70 for sensitivity or uncertainty analysis, 0.62 for background electricity and 0.59 for system boundary. The weakest criteria are therefore those that determine whether a result can be checked and how much of the life cycle it covers.

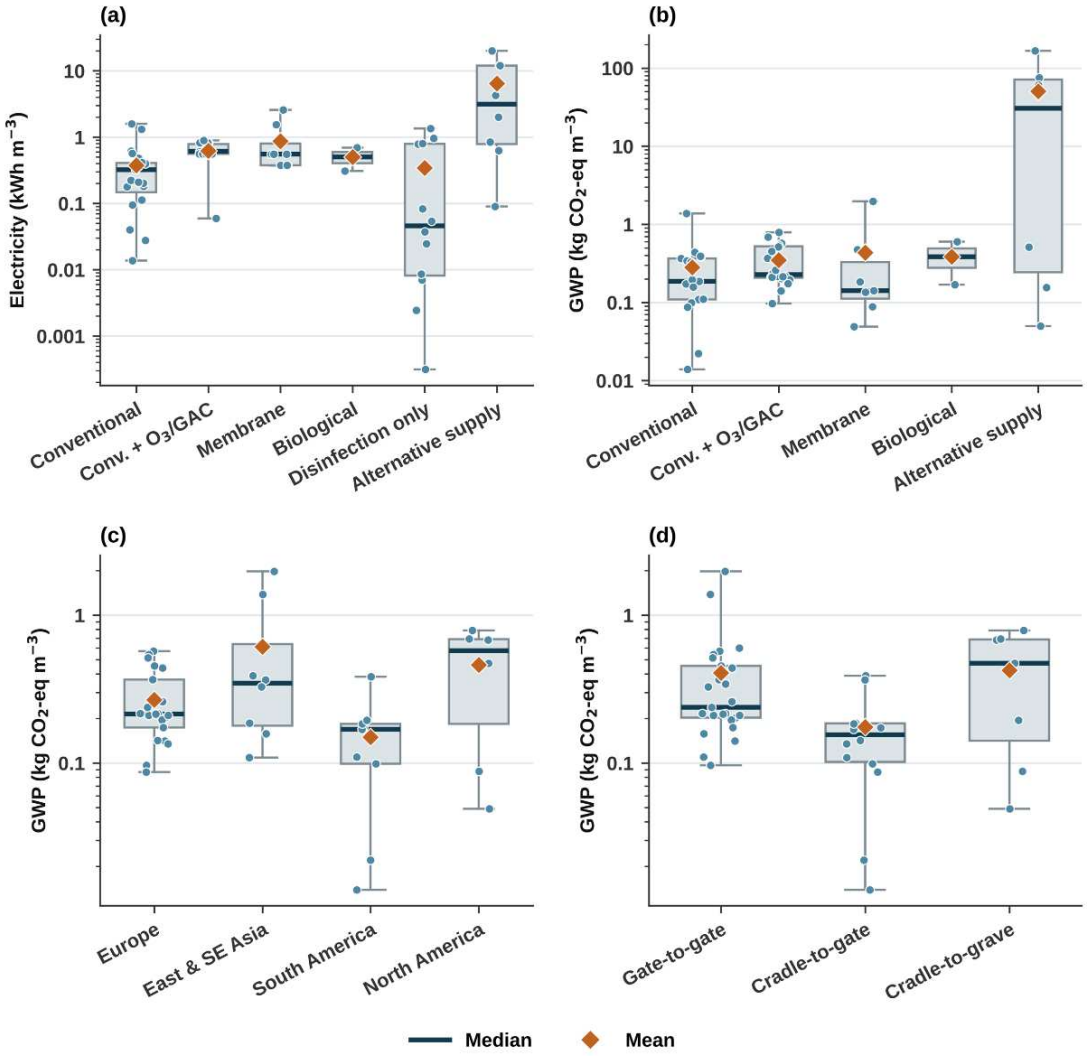


Fig. 2 *Distributions of specific electricity consumption and GWP for values admitted to the statistics (log scales). (a) Electricity by stratum. (b) GWP by stratum. (c) GWP by region, municipal plants. (d) GWP by system boundary, municipal plants. Boxes show the median and interquartile range and whiskers the full range; diamonds show the mean. Strata are defined as in Table 3; strata with a single value are omitted*

3.3 Data availability and reporting gaps

Many categories are assessed, but few are reported in a usable form. A GWP is recoverable for 62 of 112 cases (55%), 15 of them reconstructed from annual totals, unit-process tables or figure labels; specific electricity consumption for 72 (64%); and electricity carbon intensity for 55 (49%). Coverage of every other quantity is lower: acidification 27%, eutrophication 26%, fossil resource depletion 22%, stratospheric ozone depletion 18%, human toxicity 15%, freshwater ecotoxicity 14%, mineral resource depletion 10%, terrestrial ecotoxicity 9%, water depletion 9% and particulate matter formation 6%. Contribution shares are reported numerically for electricity in 26 cases (13 publications), chemicals in 21 (13) and infrastructure in 4 (3) (Table 2, Fig. 3a). Water depletion, the category most specific to a water utility, is quantified in five publications. The common claim that chemical supply dominates toxicity and resource categories therefore rests on qualitative statements and a few contribution shares, not on comparable numbers.

Table 2 *Recoverability and origin of each reported quantity across the 112 case studies*

Quantity	Reported	Derived	Carried	Assumed	Total	%	Publications
Specific electricity consumption	35	22	15	0	72	64.3	28
Global warming potential	47	15	0	0	62	55.4	19
Electricity carbon intensity	8	24	18	5	55	49.1	18
Acidification	30	0	0	0	30	26.8	11
Eutrophication	29	0	0	0	29	25.9	10
Fossil resource depletion	25	0	0	0	25	22.3	7
Stratospheric ozone depletion	20	0	0	0	20	17.9	8
Human toxicity	17	0	0	0	17	15.2	7
Freshwater ecotoxicity	16	0	0	0	16	14.3	6
Mineral resource depletion	11	0	0	0	11	9.8	4
Terrestrial ecotoxicity	10	0	0	0	10	8.9	4
Water depletion	10	0	0	0	10	8.9	5
Particulate matter formation	7	0	0	0	7	6.2	4
Electricity contribution share	26	0	0	0	26	23.2	13
Chemicals contribution share	21	0	0	0	21	18.8	13
Infrastructure contribution share	4	0	0	0	4	3.6	3

Provenance classes are defined in Section 2.2. Totals count values of any provenance; withheld values (Online Resource 1, Table S4) are included here and excluded from Table 3

Of the 50 cases without a recoverable GWP, 20 show only unlabeled bar charts, 13 use endpoint methods, 12 report relative results and 5 omit the category. Unlabeled figures are easily avoided, since a table of the same results would make 20 cases usable. Relative results cannot be compared with other studies. Endpoint-only results cannot be converted back to midpoints, so these studies stay outside quantitative synthesis however good their inventory.

An electricity carbon intensity can be obtained for 55 cases, but only 8 are tagged reported (Fig. 3b). Of the rest, 24 were derived, from a stated generation mix or by dividing a study's greenhouse-gas result by its electricity use, and 5 are assumed. The remaining 18 are carried, 12 of them because the French mix printed by (Ahmadi et al. 2016) applies to the companion papers on the same plant. Only three publications state the carbon intensity of the electricity they modeled, giving five values: 0.039, 0.108, 0.574, 0.725 and 0.848 kg CO_2-eq kWh^{-1} (Ahmadi et al. 2016; Karnaningroem and Anggraeni 2021; Ouattara et al. 2024). Two studies model a foreign grid: Saad et al. (2019) use a European average because Turkish data were unavailable, and the intensity implied by Sarraf and Deswal (2023) is about double that of the European mix they declare. In most studies, then, the footprint cannot be split between plant design and electricity supply, or transferred to another setting. Two identical plants on grids differing tenfold can report footprints differing several-fold, and a reader cannot tell this from a difference in engineering. We consider this omission a major obstacle to synthesizing the climate results.

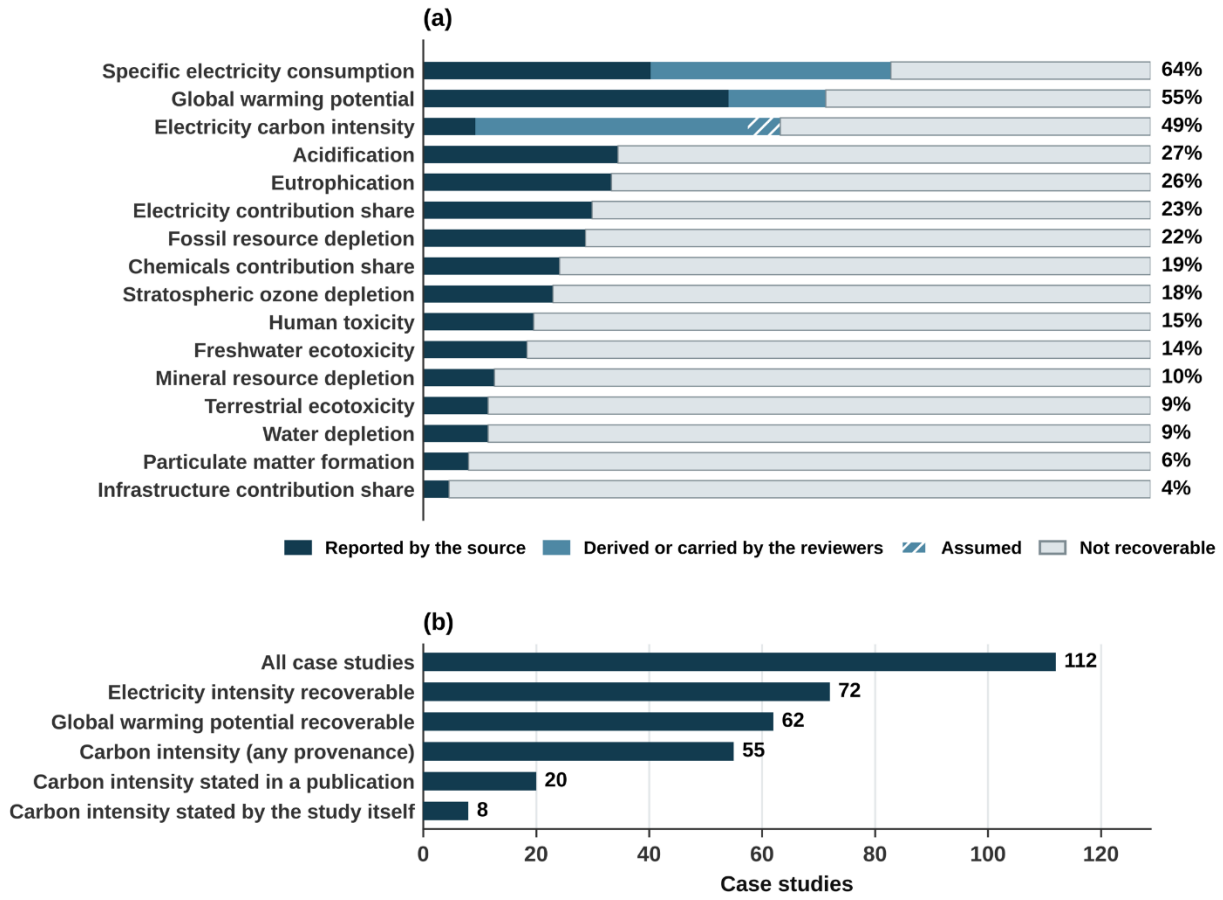


Fig. 3 *Recoverability of reported quantities. (a) Cases with a recoverable value, by provenance. (b) Cases for which an electricity carbon intensity can be obtained, and the subsets stated in any publication and stated by the study itself*

3.4 Energy and carbon intensity

Municipal plants, disinfection unit processes and alternative supply are reported separately because their functional units describe different services (Table 3, Fig. 2). The values describe the published record, not a population of plants.

Table 3 *Electricity consumption and GWP by supply family and treatment class, as median (interquartile range) [full range]*

Stratum	n	Electricity (kWh m⁻³)	n	GWP (kg CO_2-eq m⁻³)
Municipal DWTP, all	48	0.45 (0.22–0.62) [0.014–2.59]	46	0.21 (0.15–0.43) [0.014–1.98][a]
Conventional	23	0.32 (0.15–0.41) [0.014–1.58]	17	0.19 (0.11–0.36) [0.014–1.38][a]
Conventional plus ozone/activated carbon	14	0.61 (0.56–0.79) [0.060–0.90]	20	0.23 (0.21–0.52) [0.097–0.79]
Membrane filtration	8	0.55 (0.38–0.80) [0.37–2.59]	7	0.14 (0.11–0.33) [0.049–1.98][a]
Biological filtration	2	0.31; 0.69	2	0.17; 0.60
Advanced oxidation	1	0.081	0	–
Disinfection only	12	0.046 (0.008–0.79) [0.00031–1.35][b]	0	–
Alternative supply[c]	8	3.1 (0.79–12.0) [0.090–20.0]	6	0.05; 0.16; 0.51; 60.8; 75.1; 166

n varies because not all cases report both quantities. Values for strata with fewer than three cases are listed individually. Withheld values and their reasons are given in Online Resource 1, Table S4, and a sensitivity analysis using baselines only and one value per physical system in Table S9. [a] Includes the three Sharaai et al. (2010) trains (0.33, 1.38 and 1.98), which are reported as CO_2 rather than CO_2-eq; the 1.98 maximum is one of these. [b] Includes four groundwater systems of Zúñiga et al. (2023) whose only treatment is chlorination but whose electricity includes well abstraction (0.79–1.35 kWh m⁻³); the eight stand-alone disinfection unit processes have a median of 0.017 kWh m⁻³ [0.00031–0.083]. [c] Household reverse osmosis, household well, rainwater harvesting, bottled water and one desalination plant (electricity 4.3 kWh m⁻³; no GWP)

Municipal cases have a median electricity consumption of 0.45 kWh m^{-3} (interquartile range, IQR, 0.22–0.62) and a median GWP of 0.21 kg CO_2-eq m^{-3} (IQR 0.15–0.43), with right-skewed 189- and 142-fold ranges (Table 3). One electricity value was withheld (Rodriguez et al. 2016): at 0.0026 kWh m^{-3} it is below the 0.01 kWh m^{-3} lower bound, and keeping it would widen the range to about 1,000-fold. Counting each physical system once lowers the median electricity to 0.31 kWh m^{-3} (n = 25 systems), because many Seine scenarios weight the case-level distribution, while the median GWP hardly changes (0.20 kg CO_2-eq m^{-3}, n = 20) (Online Resource 1, Table S9). Regional median electricity is 0.56 kWh m^{-3} in Europe (n = 20), 0.36 in East and Southeast Asia (n = 15), 0.35 in South America (n = 8) and 0.55 in North America (n = 3), and median GWP is 0.21 (n = 21), 0.35 (n = 8), 0.17 (n = 9) and 0.58 (n = 6) kg CO_2-eq m^{-3} respectively (Fig. 2c). The highest median comes from six scenarios of one Canadian study, four of which substitute the French or United States grid. The regional ordering does not follow grid carbon intensity and changes when each system is counted once (Table S9), so these data give little support for using region as a proxy for grid carbon intensity.

Median electricity rises from conventional trains (0.32 kWh m^{-3}, n = 23) through membrane filtration (0.55, n = 8) to trains with ozonation or activated carbon (0.61, n = 14), as process engineering would predict; the strata overlap heavily and are confounded with region, so this is not an estimate of a technology premium. GWP follows a different order. Membrane filtration has the lowest median (0.14 kg CO_2-eq m^{-3}) despite the second-highest electricity use, and trains with ozonation or GAC the highest among strata with at least three values (0.23, against 0.19 for conventional trains). Two features probably account for this: the membrane stratum includes the nanofiltration scenarios of Bonton et al. (2012) on the hydroelectric Quebec and nuclear-dominated French mixes (0.049 and 0.088 kg CO_2-eq m^{-3}), and the GAC stratum carries a large burden from activated carbon production. The pattern holds when each system is counted once (Table S9).

Twelve of the 18 disinfection-only cases give a usable electricity intensity (median 0.046 kWh m^{-3}, IQR 0.008–0.79). The four groundwater systems of Zúñiga et al. (2023) use only chlorination but report 0.79 to 1.35 kWh m^{-3} because their electricity includes well abstraction; the eight stand-alone unit processes have a median of 0.017 kWh m^{-3}, more than an order of magnitude below complete trains; for ultraviolet (UV) disinfection in (Jones et al. 2018a) this covers lamp energy only. The only four GWP values (Zúñiga et al. 2023) are double reconstructions and are withheld. Demir et al. (2024) report a 172-fold span across four methods at one supply, from 3.1×10^{-4} kWh m^{-3} for gaseous chlorination to 5.4×10^{-2} for UV LED, and find the low-pressure UV lamp lowest in all eighteen categories, partly because producing a UV LED lamp has 13 to 2,860 times the impact. Nitkiewicz and Jachimowski (2019) attribute essentially all of the impact of gaseous chlorination to the chemical and 76% of a UV and electrolytic hypochlorite route to electricity. Salazar et al. (2022) attribute 87 to 94% of climate impact at two plants to coagulation and flocculation chemicals, and Jones et al. (2018a) find chlorine preferable to UV in most modeled cases. Because disinfection uses little of a plant's energy, these differences are large in relative terms but small in absolute terms.

Centralized treatment has a lower footprint than most decentralized alternatives in this corpus. Of two studies of household reverse osmosis (Gani et al. 2023; Garfí et al. 2016), the first finds that a household unit (0.15 kWh m^{-3} on top of 0.48 kWh m^{-3} at the plant) raises impacts by 10 to 24%; the second reports 2.0 kWh m^{-3}, but its GWP does not match that electricity use and is withheld. Hybrid mains-plus-rainwater systems in Brazil report 0.44 and 0.55 kg CO_2-eq m^{-3} against 0.195 for mains supply (Silva et al. 2023), but they mix potable water with untreated roof runoff and are kept out of the statistics. Bottled water lies far outside the range of any treatment technology: Zúñiga et al. (2023) report 20 kWh m^{-3} and 166 kg CO_2-eq m^{-3}, about 550 to 2,350 times their network tap water depending on the category, and Garfí et al. (2016) report 75.1 kg CO_2-eq m^{-3} for polyethylene terephthalate (PET) bottles and 60.8 for reusable glass.

3.5 Effect of grid carbon intensity

If grid carbon intensity governed DWTP footprints, plants on low-carbon grids would report low footprints once electricity use is accounted for. A cross-study test is not possible: only three publications state their carbon intensity, and back-calculated values would largely restate arithmetic. Comparisons within one study avoid this when the system and inventory are fixed and only the electricity supply or the treatment train changes. We found seven (Online Resource 1, Table S8): six substitute the electricity supply (Ahmadi et al. 2016; Baltrocchi et al. 2024; Bonton et al. 2012; Jones et al. 2018a; Roth et al. 2022; Saad et al. 2019) and one compares trains on one grid (Sharaai et al. 2010). Because the functional unit, boundary, database and characterization method stay constant within each paper, the difference can be attributed to the variable that changed.

Bonton et al. (2012) substituted three grid mixes into matched nanofiltration and conventional+GAC trains. The nanofiltration train varied 9.7-fold (0.049–0.473 kg CO_2-eq m^{-3}) and the conventional+GAC train only 1.16-fold (0.68–0.79), because the burden of the second lies in GAC manufacture and sludge management. Similarly, at a large conventional plant where pumping takes 84.9% of electricity, wind or solar supply reduces GWP by 29 to 84% (Saad et al. 2019). Roth et al. (2022) compared UV/hydrogen peroxide advanced oxidation with low-pressure reverse osmosis for micropollutant removal. On aggregated single scores (not GWP), the ranking reverses at about 80% renewable electricity, for hydroelectricity and wind but not solar, because reverse osmosis uses 0.38 kWh m^{-3} against 0.08 for advanced oxidation, whose burden lies in GAC and hydrogen peroxide. On the utility's contracted supply (100% renewable, 94% hydroelectric), advanced oxidation has a 50 to 120% higher impact; on the Swiss or European mix the ranking reverses.

Jones et al. (2018a) compared four electricity supplies for one disinfection duty, from a high-impact grid to a hypothetical zero-impact supply. The supply changes every impact category for energy-driven UV but affects chlorine comparatively little, and the contact-zone material of the chlorine train matters about as much, with steel baffles accounting for up to 80% of its infrastructure impacts. (Baltrocchi et al. 2024) show that a cleaner supply can move burden elsewhere: fully photovoltaic electricity reduces environmental indicators by about 53% at an arsenic-removal plant but raises terrestrial ecotoxicity and the monetized environmental cost. In these comparisons, the effect of the grid depended on the plant. It was large for membranes, pumping-intensive schemes, ozone generation and UV disinfection, and much smaller for trains driven by chemicals and adsorbents. For a utility, the more useful question is what share of its footprint comes from electricity, a share most studies do not report.

Ahmadi et al. (2016) tabulate ten electricity carriers for one French plant, from 0.0126 kg CO_2-eq kWh^{-1} for run-of-river hydroelectricity to 1.211 for hard coal, the only within-study table of carriers with stated carbon intensities in the corpus (Online Resource 2, grid_ladder sheet). At 0.824 kWh m^{-3}, the electricity-related footprint alone would range from 0.010 to 0.998 kg CO_2-eq m^{-3}, against a modeled total of 0.21 on the French mix, that is, from about 5% of the current total to more than four times it. The paper's headline 54% reduction is not a grid effect, because the optimized configuration also eliminates virgin activated carbon, switches the carbon producer's process heat to wood cogeneration and cuts the coagulant dose from 61 to 20 ppm. The heat substitution alone cuts the footprint by 33% at unchanged operating cost, because activated carbon falls from 18.10 to 0.77 kg CO_2-eq kg^{-1} (virgin) and from 8.42 to 0.76 (regenerated), although human toxicity and land use worsen. It is the largest reduction from a single non-grid change reported in the corpus. Other design and operating changes are of a similar order. Sharaai et al. (2010) report 0.397 kWh m^{-3} for a clarifier train, 1.581 for dissolved air flotation and 2.586 for ultrafiltration at one plant on one grid, a 6.5-fold difference. Raising pump efficiency from 60 to 90% reduces GWP by 15 to 24% (Saad et al. 2019), and changing the balance of powdered activated carbon and coagulant at the Seine plant moves GWP from 12% below to 90% above its base case (Mery et al. 2014). These choices lie with plant designers and operators, within the limits set by raw-water quality and treatment objectives.

3.6 Contribution analysis

Across the 26 cases with a numeric electricity share, the share ranges from 3.5% to 100% (median 59%, IQR 30 to 84%), and from 4% to 86% within conventional plants, a range almost covered by the four plants of one Colombian study (Rodriguez et al. 2016), whose shares are used as printed. The spread is consistent with differences in hydraulic configuration and coagulant demand, although the studies do not report lift or raw-water quality consistently enough to test this. Few publications report pumping separately. Saad et al. (2019) attribute 84.9% of plant electricity to pumping. At the French plant, Ahmadi and Tiruta-Barna (2015) attribute 56% to ozonation and 38% to pumping against an 85 m lift; that pumping share (0.31 kWh m^{-3}) against a hydraulic requirement of 0.23 kWh m^{-3} implies a wire-to-water efficiency of about 74%. For pumping-driven processes the footprint follows the product of energy demand and grid carbon intensity; for reagent-driven processes it does not.

Chemical supply is the second main contributor and the first in chemically intensive plants. Coagulant dose varies independently of treatment class, from 7 g m^{-3} of polyaluminum chloride (Thi Thuy Duong et al. 2024) to 70 g m^{-3} of alum (Mohamed-Zine et al. 2013); the second plant uses the higher dose on raw water below 3.5 NTU, so dose seems to reflect operating practice and coagulant type as well as water quality. Barjoveanu et al. (2019) attribute 35 to 100% of impact to ferric chloride depending on the category, and Jones et al. (2018b) attribute 55 to 80% of every TRACI category to alum and caustic for a modeled utility.

Activated carbon deserves separate mention because it is often the largest non-electricity burden in the trains that use it, yet most studies merge it with other chemicals. GAC production accounts for 52% of climate change and 62%

of fossil depletion at the French plant (Ahmadi and Tiruta-Barna 2015), and Roth et al. (2022) attribute 54 to 70% of the aggregated impact of advanced oxidation to GAC and 27 to 39% to hydrogen peroxide, against 3 to 4% to electricity. The relevant choices are the virgin fraction, the regeneration frequency and the carbon producer's process heat, which grid decarbonization does not change. The same literature gives a clear case of an upgrade whose energy penalty outweighs its chemical saving: pre-ozonation before biofiltration saves alum worth up to 0.005 kg CO_2-eq m^{-3} but ozone generation costs up to 0.09, so the ozonated train has impacts up to 145% higher than the reference (Jones et al. 2018b). Whether such an upgrade pays depends on grid carbon intensity, yet the paper names no grid.

For midpoint categories other than GWP, chemical and material supply chains dominate and the grid matters less. Aluminum sulfate contributes to freshwater ecotoxicity, human toxicity and mineral resource depletion (Abulameer et al. 2024), and replacing it with ferric sulfate at the Pilsen plant reduces ozone depletion by five orders of magnitude, freshwater eutrophication 28-fold and mineral resource use eightfold, while GWP falls by only 5% (Klimtová et al. 2025). Ozone depletion is also associated with membrane manufacture and electrolytic hypochlorite generation. Ribera et al. (2014) pair a nanofiltration LCA with a human health risk assessment, one of the few studies to weigh the benefits of treatment against its environmental cost, and Jones et al. (2013) find shipping and fuel production, not electricity, to be the main contributors for two arsenic removal technologies. These results cannot be inferred from the climate findings, and coverage is lowest for exactly these categories, so the claim that chemicals dominate non-climate impacts is plausible but untested with comparable numbers.

3.7 Limitations

The corpus is limited to studies retrieved by the stated search strings; studies treating drinking water only as part of a whole urban water system were excluded (16 at eligibility), and studies indexed under other terms may have been missed. Defining physical systems and independent assessments involves judgment, so every assignment is recorded in Online Resource 2. Some values were read from figure labels or reconstructed from annual totals, and their provenance tags record how. Case-level distributions give more weight to systems with many scenarios, and Table S9 shows which conclusions depend on this.

4 Conclusions and Future Perspectives

4.1 Conclusions

We re-extracted 37 LCAs of drinking water treatment plants at plant level. The 112 cases describe 51 physical systems but rest on 30 independent assessments, so counting publications overstates the independent evidence by about a quarter. Usable numbers are scarce: 55% of cases have a recoverable GWP and 64% an electricity intensity, no other midpoint category exceeds 27%, and water depletion reaches 9%. Only three publications state the carbon intensity of the electricity they modeled, so most footprints cannot be split into plant design and electricity supply.

Seven within-study comparisons show that grid leverage depends on the treatment train. It is large for electricity-driven trains such as membranes, UV, ozone and pumping-intensive schemes, where the electricity supply can change GWP by up to an order of magnitude, and small for chemical- and adsorbent-driven trains. Process, hydraulic and supply-chain choices also have large effects and lie with plant designers and operators: at one plant on one grid, electricity use varied 6.5-fold between trains, and at another, changing only the activated carbon supplier's process heat cut the footprint by a third. Non-climate impacts appear to be driven by chemical and material supply chains, which grid decarbonization does not address. Decarbonizing drinking water treatment therefore depends on plant design and material supply as well as on cleaner electricity, in proportions that differ between plants.

4.2 Future Perspectives

Future DWTP LCAs should report the minimum set below, above all the carbon intensity of the modeled electricity (with dataset and version) and specific electricity consumption with raw-water pumping separated. Four gaps stand out. No study is consequential: none uses marginal emission factors or models how the grid will change over the plant's lifetime, and only one compares a contracted supply with the national mix (Table S8). Water depletion is quantified in only five publications. Sub-Saharan Africa, Central Asia and Oceania are unrepresented, and low- and lower-middle-income countries nearly so. Assessments of new plants are scarce compared with re-analyses of existing inventories, and journals and reviewers can help by asking whether a plant has been assessed before.

- Report the carbon intensity of the electricity supply actually modeled, in kg CO_2-eq kWh^{-1}, with the dataset named and versioned.
- Report specific electricity consumption in kWh m^{-3}, separating raw-water pumping from in-plant process energy.
- State the production volume used to normalize annual totals, and the period it covers.
- Publish characterized results as numbers in a table, not solely as figures.
- Report at least one midpoint climate indicator even where an endpoint method is the primary choice.
- State the functional unit once, unambiguously, and check it against the inventory.
- State explicitly whether and how construction is modeled.
- Report numeric contribution shares for electricity, chemicals, infrastructure, transport and sludge, each naming its impact category.
- State whether the plant has been assessed before, and what has changed.

Statements and Declarations

Ethics approval

This study is a review of previously published literature and involved no human participants or animals; ethics approval was not required.

Consent to participate and consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Author contributions

Ankita Pokhrel: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. Bernard Lassimo Diawara: Investigation, Data curation, Validation. Yateh Mohamed: Investigation, Data curation. Xianwei Zeng: Resources, Validation. Yulin Tang: Conceptualization, Supervision, Writing – review and editing, Funding acquisition.

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Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files:
Online Resource 1 Search strategy, extraction, appraisal and supporting evidence (Tables S1–S9, Fig. S1)
Online Resource 2 Plant-level case-study dataset with the source and provenance of every value (.xlsx)

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