

RESEARCH ARTICLE

CO₂e footprint and eco-impact of ultralow phosphorus removal by hydrous ferric oxide reactive filtration: A municipal wastewater LCA case study

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Abstract

Dual upflow reactive filtration by a slowly moving sand bed with continuously renewed, hydrous ferric oxide-coated sand is used for removing polluting substances and for meeting the ultralow 0.05 mg/l total phosphorus discharge permit limits at a 1.2 million liters per day (0.32 million gallons per day) water resource recovery facility in Plummer, Idaho, in the United States. A life cycle assessment (LCA) of this reactive filtration installation was carried out to assess the environmental hotspots in the system and analyze alternative system configurations with a focus on CO₂ equivalent (CO₂e) global warming potential, freshwater and marine eutrophication, and mineral resource scarcity. “What if” scenarios with alternative inputs for the energy, metal salts, and air compressor optimization show trade-offs between the impact categories. Key results that show a comparative reduction of global warming potential include the use of Fe versus Al metal salts, the use of renewable energy, and the energy efficiency benefit of optimizing process inputs, such as compressor air pressure, to match operational demand. The LCA shows a 2×10^{-2} kg CO₂e footprint per cubic meter of water, with 47% from housing concrete, and an overall freshwater eutrophication impact reduced by 99% versus no treatment. The use of renewable hydropower energy at this site isolates construction concrete as a target for lowering the CO₂e footprint.

Practitioner Points

- The main LCA eco-impact hotspots in this dual reactive filtration tertiary treatment are construction concrete and the ferric sulfate used.
- Iron salts show smaller impact in global warming, freshwater eutrophication, and mineral resource scarcity than “what if scenario” aluminum salts.

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- The energy mix for this site is predominantly hydropower; other energy mix “what if” scenarios show larger impacts.
- Operational energy efficiency and thermodynamic analysis show that fine tuning the air compressor helps reduce carbon footprint and energy use.
- LCA shows a favorable 2 x 10⁻² kg CO₂e/m³ water impact with 99% reduction of freshwater eutrophication potential versus no treatment.

KEYWORDS

carbon footprint, environmental impacts, eutrophication, life cycle assessment, phosphorus removal, reactive filtration, wastewater treatment

INTRODUCTION

Increasing global water demand continues mainly due to rising use in the industrial and domestic sectors (UNDP, 2019). This demand is driven by a growing population, socioeconomic development, and changing consumption patterns. Estimates show that 380 billion m³ of wastewater is produced globally every year, and it is expected to increase by 24% by 2030 and 51% by 2050 (Qadir et al., 2020). In the face of climate change, challenges in water scarcity and wastewater impacts on water quality are exacerbated.

There is an increased understanding of a *climate change* ↔ *eutrophication* feedback loop (Meerhoff et al., 2022), and this evidence heightens the need for nutrient removal water treatment technologies that have minimal CO₂ equivalent footprints (CO₂e; global warming potential [GWP]) to interrupt this feedback (Beaulieu et al., 2019; OECD, 2013). Studies on the interrelations of climate change and nutrients show that phosphorus release to surface waters will increase due to overall increased precipitation and soil erosion caused by extreme rainfall or snowmelt events (Liu et al., 2020; Ockenden et al., 2017). Increased temperatures accelerate algal growth, favoring harmful species such as cyanobacteria (Glibert, 2020). As warming speeds up internal nutrient release in lakes and diminishes the resilience of biotic communities to eutrophication, eutrophic aquatic systems become significant sources of greenhouse gases (GHG) to the atmosphere (Meerhoff et al., 2022).

Water quality deterioration has environmental, human health, and economic costs. Nitrogen and phosphorus nutrient loads are the key factors contributing to harmful algal blooms (HABs) in freshwater and coastal zones worldwide (Carpenter, 2008; Pelley, 2016; Schindler et al., 2016). These aquatic ecosystem nutrient impacts are multifactorial, and significant pollution vectors can include point sources such as municipal and industrial wastewater discharges and nonpoint sources

such as urban and agricultural runoff. Nitrogen and phosphorus studies in freshwater lakes find that phosphorus is considered the limiting nutrient in HABs in part, due to the biotic–abiotic nitrogen cycle (Schindler et al., 2008, 2016).

Wastewater treatment technologies play a crucial role in preventing toxic algal blooms and meeting sustainability objectives, such as the United Nations Sustainable Development Goal 6 (SDG 6) (Tortajada, 2020; UNDP, 2018). However, water resource recovery facilities (WRRF) also have a significant impact on the environment because of the materials used in their construction and the energy and consumable process inputs used during their operation.

WRRF are highly regulated elements of civil infrastructure. The National Pollution Discharge Elimination System (NPDES) is the main instrument enforcing the Clean Water Act in the United States (CWA, 1972; USEPA, 2022a). An NPDES permit limits pollutant discharges and defines monitoring and reporting requirements tailored to the operations of each permit holder (USEPA, 2022a). Permits are issued based on the technology available (technology-based effluent limits) and depending on the quality of the receiving water body and its designated uses (water quality-based limits) (USEPA, 2010).

As WRRF are a key public health and environmental quality response to anthropogenic impact, it is of great value to fully understand and quantify the broad range of impacts from facility construction and operation. Life cycle assessment (LCA) is considered the most integrated and comprehensive tool available for evaluating the environmental sustainability of new technologies. LCA quantifies sustainability-related metrics from a systems perspective to identify hotspots associated with the system. It captures the trade-offs across various environmental impact categories and serves as a decision-support tool for planning alternative future scenarios (Corominas et al., 2020; Lundie et al., 2004). LCA was developed as

an energy analysis tool and evolved into a comprehensive environmental burden analysis and life cycle costing approach (Guinee et al., 2011). Several studies demonstrate that it is an efficient approach for analyzing the environmental impacts of different technologies for nutrient removal, thereby supporting design and operation decisions (Corominas, Foley, et al., 2013).

As communities and industry prepare to replace first- or second-generation WRRF infrastructure with newer technologies capable of greatly reducing nutrient efflux to the environment, it is critical that they be designed and operated to have minimal environmental impacts of greenhouse causing gases (i.e., have a small carbon footprint) and that their impacts on limited resources be accounted for. LCA is a tool for a standardized accounting of primary and secondary impacts and thus can support informed decision-making for reduced environmental impacts (Corominas et al., 2020; Guinee, 2002). The accuracy of LCA results is dependent on the quality of input data, and if laboratory-scale data are used for the environmental impact assessment in technology development, the LCA results may have limited usefulness for real-scale application (Corominas, Foley, et al., 2013).

Several LCA studies cover different aspects or stages of wastewater treatment, including nutrient removal, various tertiary processes, resource recovery, or water reuse opportunities (Canaj et al., 2021; Coats et al., 2011; Garfi et al., 2016; Hoibye et al., 2008; Lundie et al., 2004; Munoz et al., 2009; Rahman et al., 2016; Risch et al., 2021; Zhang et al., 2010).

For example, a comparative LCA study considered three alternatives for wastewater treatment in small communities in Spain serving 1500 people. The treatment process was designed to optimize biological oxygen demand (BOD₅) and total suspended solids (TSS) removal. This study, using “hypothetical wastewater treatment plants designed by an engineering company,” revealed that nature-based systems, such as hybrid constructed wetland and high-rate algal pond systems, had a significantly lower environmental impact than conventional activated sludge systems due to electricity and chemicals consumption (Garfi et al., 2016).

An LCA by Rahman et al. (2016) of three types of WRRFs targeting nitrogen and phosphorus removal demonstrated that advanced technologies significantly decrease potential local eutrophication. However, they calculated that the use of electricity and chemicals for the advanced treatment, including multistage enhanced processes and reverse osmosis, increased indirect eutrophication and contributed to other environmental and health impacts, such as GWP, ecotoxicity, ozone depletion, and acidification. The study showed that average

eutrophication potential (EP) might be reduced by about 70% when targeting TP = 0.1 mg/l with advanced treatment technologies instead of the conventional first-level treatment with TP = 1 mg/l and that more advanced tertiary treatment processes targeting TP = 0.01 mg/l may only offer an additional 15% net reduction in EP because of the secondary impacts associated with technology implementation and operation (Rahman et al., 2016).

Niero et al. (2014) conducted an LCA study comparing four types of WRRFs in Denmark and observed that fossil-based electricity use has the greatest impact on the environment in terms of climate change and fossil depletion impact categories. Based on this, the authors suggested that phosphorus recycling to agricultural soils is a more sustainable alternative than sludge incineration (Niero et al., 2014).

The process and mechanism of the reactive filtration water treatment technology with hydrous ferric oxide (HFO)-coated sand has been described in detail (Newcombe, Rule, et al., 2008; Newcombe, Strawn, et al., 2008). The technology is capable of total phosphorus (TP) discharge levels in the range of 0.010 mg/l and thus provides an approach to addressing the need for ultralow phosphorus discharge in the management of HABs in many receiving waters and has been successfully deployed at scale into civil infrastructure for wastewater treatment (Möller, 2008; Möller et al., 2010, 2013; Möller & Newcombe, 2011). There are about 60 installations of wastewater treatment reactive filtration technology that have been operating and serving communities and industries in North America, South Korea, and the United Kingdom for several years. One of these installations where reactive filtration tertiary wastewater treatment technology can reduce phosphorus to ultralow levels is the facility in the community of Citronelle, Alabama, where the NPDES discharge permit limit was set at 0.022 mg/L TP (USEPA, 2022a). However, the broader environmental costs of this relatively new nutrient removal technology still need to be assessed.

The goal of the present research is to assess the life cycle environmental impacts of tertiary dual reactive filtration at an WRRF that is designed and operated to remove phosphorus to ultralow levels. Specific objectives are to use LCA to identify treatment facility build and operation processes that have global warming potential, freshwater and marine eutrophication potential, and mineral resource extraction impacts and evaluate the effects of alternative operation and input scenarios on these environmental impacts for more sustainable wastewater treatment and resource recovery.

METHODOLOGY AND DATA

Implementation of the LCA for this study follows the guidelines outlined by the International Organization for Standardization (ISO) ISO 14040 *Principles and Framework* and ISO 14044 *Requirements and Guidelines* (ISO, 2006a, 2006b) LCA standards. The input/output data were collected either through direct measurements at the facility in Plummer, Idaho, by personal communication with the facility operators and relevant regulatory documents or from operation and maintenance documentation for the facility. In total, 2196 input/output data elements were used in the LCA model calculations.

Wastewater treatment system description

The City of Plummer WRRF is a publicly owned municipal facility located in the Coeur D'Alene Tribe Reservation in Idaho, USA. It serves a resident population of 1017. The design flow of the facility is 1.2 million liters per day (0.32 million gallons per day, MGD), and the reported flows from the facility range from 0.15 to 1.5 million liters per day (0.04–0.4 MGD) (average monthly flow) with an average daily flow of 0.38 million liters per day (0.1 MGD). No industries are discharging to the facility (USEPA, 2020a). According to the Coeur d'Alene Tribe Water Quality Standards, designated beneficial uses for the treated water include industrial and agricultural water supply, wildlife habitat, aesthetics, recreational, and cultural use (IDEQ, 2022a; USEPA, 2019).

The Plummer NPDES permit sets effluent limitations and monitoring requirements for various parameters important for water quality. The TP discharge limit is set to 0.05 mg/L for April to November and 0.1 mg/L for December to March (USEPA, 2020b).

The facility discharges Class B recycled water, defined as “oxidized, coagulated, clarified, and filtered, or treated by an equivalent process and adequately disinfected” (IDEQ, 2022b) to Plummer Creek in the St. Joe River Subbasin, flowing into Chatcolet Lake at the southern end of the Coeur d'Alene Lake. Annual phosphorus loading in Coeur d'Alene Lake was estimated in 2009 at 144,000 kg/year (IDEQ & CDA Tribe, 2009). In 2021, the water quality of Coeur d'Alene Lake became the focus of a US National Academies of Sciences committee exploring the relationship of nutrient pollution to heavy metal release from mining-impacted sediments (NAS, 2022); thus, understanding and regulating WRRF nutrient inputs are of high importance.

A dam-controlled, phosphorus-impacted natural water body, Coeur d'Alene Lake is about 40 km long and 1–5 km wide, and it drains from the north by the

Spokane River. It is fed from the south by the St. Joe River and southeast by the mining-impacted Coeur d'Alene River. These two feed rivers combined provide over 75% of the TP load to the lake, with less than 10% of that load originating from municipal WRRFs, which was 8200 kg/year in 2009–2017 (IDEQ & CDA, 2020). Although the contribution of the Plummer WRRF flow and annual phosphorus load is small compared with the Coeur d'Alene Lake watershed's overall inflow phosphorus load, the St. Joe River delta region into Coeur d'Alene Lake called Chatcolet Lake is eutrophic and often becomes anoxic (USEPA, 2020a). Plummer Creek, the outfall for the Plummer WRRF, is dominated by facility effluent in the summer months, and receiving water quality modeling by the US Environmental Protection Agency (USEPA) yielded the low water quality-based effluent TP limit of 0.05 mg/L to help prevent harmful algae blooms in Chatcolet Lake (USEPA, 2020b). Tribal authorities also guide regional water quality management, and Coeur d'Alene Tribal Reservation Water Quality Standards protect Plummer Creek water, as well as the lower third of Coeur d'Alene Lake for agricultural, aquatic life, cultural, and recreational uses.

The facility provides advanced treatment of wastewater using an extended aeration-activated sludge process with an anaerobic tank and fermenter for biological phosphorus removal. After the wastewater undergoes biological treatment, additional phosphorus removal is provided by the reactive filtration process (Figure 1).

Secondary treated wastewater is filtered by a slowly moving sand bed configured for reactive filtration (see Figure 1). Ferric iron added to a backwashed moving bed sand filter continuously creating and removing an HFO coating on sand grains that serve as a high surface area adsorption site for removing polluting substances, such as phosphorus and other contaminants (Newcombe, Strawn, et al., 2008). Iron-rich reactive filtration reject-recycling return to primary treatment at this site aids overall TP

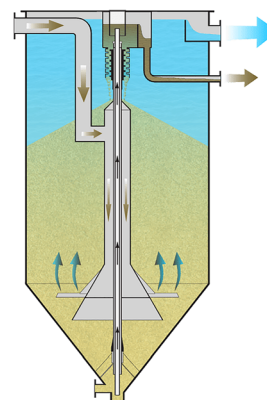


FIGURE 1 Continuous backwash moving bed sand filter (reprinted from <https://nexom.com/bluepro> with permission)

removals (Möller & Newcombe, 2011; Newcombe, Rule, et al., 2008; Newcombe, Strawn, et al., 2008). The facility follows tertiary RF with ultraviolet disinfection before discharge. Waste sludge is dewatered using belt filter presses (USEPA, 2022b). Figure 2 shows a simplified process diagram for Plummer and the reactive filtration system, as well as the site measured share of the energy used by different components within the system.

In the reactive filtration process, ferric sulfate is pre-reacted with water immediately before moving bed sand filtration to yield adsorptive HFO-coated media. The high adsorptive capacity of HFO and large reactive surface area with a continuously regenerating coating of sand with HFO enable about 90% TP removal with each filter pass, addressing the primary nutrient causing freshwater eutrophication (Newcombe, Rule, et al., 2008; Newcombe, Strawn, et al., 2008; Schindler et al., 2016). Specific iron–phosphorus chemical adsorption mechanisms and engineering details involved in the reactive filtration process are described in Newcombe, Rule, et al. (2008) and Newcombe, Strawn, et al. (2008).

The discharge permit compliance database US EPA Enforcement and Compliance History Online (ECHO) shows that the 2020–2021 average effluent concentration TP at the Plummer WRRF during this study was well below the 0.05 mg/L NPDES permit limits and normally

performed at TP < 0.005 mg/L in the 18 months preceding this analysis (USEPA, 2022a). The TP concentration of the average clarifier influent entering this tertiary reactive filtration process is nominally 1–2 mg/L, according to facility operators. Hence, in this case, dual reactive filtration technology is removing about 99% of phosphorus, consistent with prior work (Newcombe, Rule, et al., 2008; Newcombe, Strawn, et al., 2008), and thus decreasing TP concentrations in this process effluent to less than 0.012 mg/L oligotrophic level considered at the watershed scale (Carlson, 1977; Carlson & Simpson, 1996).

LCA goal and scope

The goal of this study is to assess the environmental impacts of the dual upflow reactive filtration targeted at phosphorus removal at the WRRF in Plummer, Idaho, in the United States, and explore the opportunities for process optimization. We identified three sub-objectives: (i) to identify environmental hotspots in the operation, (ii) to consider and analyze alternative scenarios with system modifications compared with the baseline, and (iii) to determine the most environmentally optimal configuration based on the life cycle impact assessment (LCIA) results.

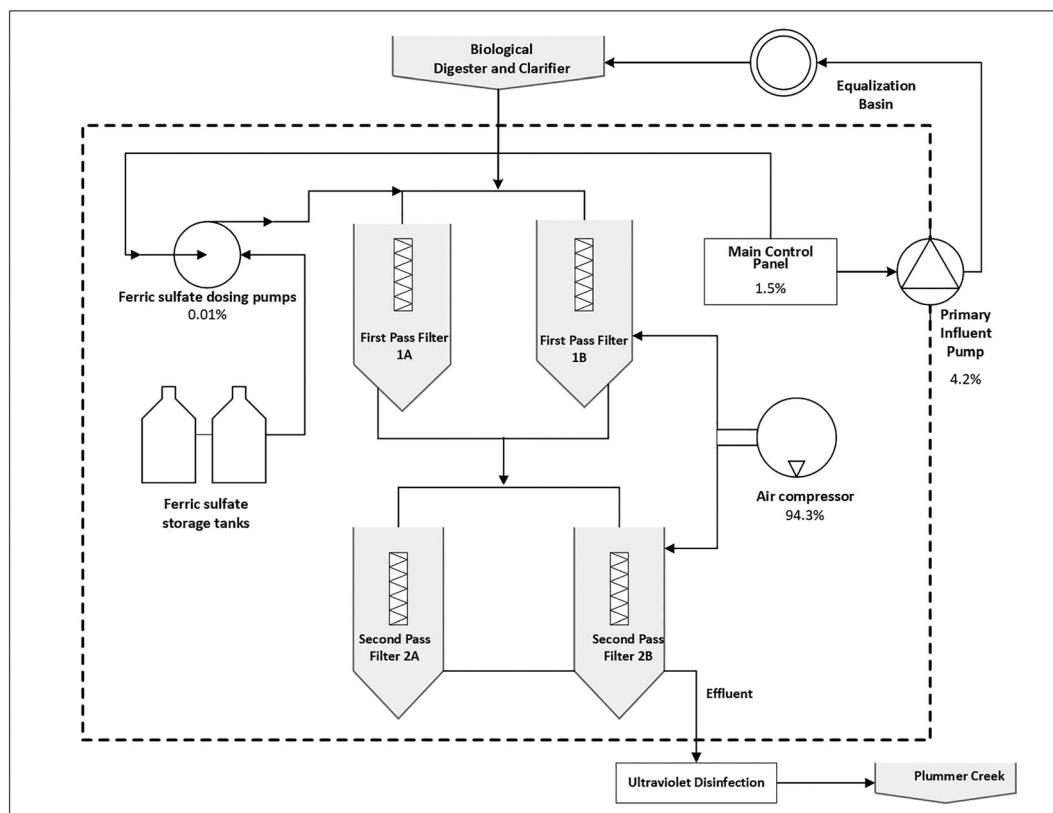


FIGURE 2 Physical system boundaries for the reactive filtration LCA at Plummer, ID, using continuous dual backwash upflow HFO sand filters. The dashed line shows the LCA system boundaries; the outline solid line shows the WRRF processes that are beyond this LCA.

System boundaries

The inputs and outputs in wastewater treatment systems usually include resources and energy needed for producing capital goods, such as the infrastructure and equipment, energy production, and chemicals consumed in the treatment process (Corominas et al., 2020). Transportation of construction and operation materials was not accounted for because transportation was used during construction work in 2010 and therefore difficult or impossible to accurately reconstruct. Additionally, more recent transportation data for operating materials vary with changing supply chains, and transportation can be small, compared with their overall manufacturing impact. Jørgensen et al. (1996) reviewed different LCAs and found that relative contribution of transport can be more than 10% and its relative contribution strongly depends on the type of product or service studied. In that analysis, transport contributions to life cycle impacts are more important for raw commodity products rather than highly processed materials because of processing inputs and their related impacts. We assume that impact underreporting due to neglecting unknown transportation contributions would be less than 5% for manufactured construction goods and operating materials impacts and that this assumption would not affect the identification of LCA hotspots in this analysis. The system boundary for this LCA included influent pumping to the tertiary RF treatment facility up to effluent discharge (Figure 2).

Functional unit

A functional unit defines qualitative and quantitative features (i.e. “what” and “how much”) and acts as a common denominator for everything used in the process or product. Thus, a common and practical functional unit can ensure comparability of LCA results (Corominas et al., 2020; ISO, 2006a; Rebitzer et al., 2004). Functional units used in LCA literature for wastewater treatment vary, including the volume of treated water, the mass of sludge, person equivalent, pollution loads in the influent, and eutrophication potential reduction (kg PO_4^{3-} as P removed) (Corominas et al., 2020; Rodriguez-Garcia et al., 2011).

For this LCA study, we use 1 m^3 of influent wastewater as the functional unit. The construction phase inventory was completed for a 20-year design life, which is typical for wastewater works in the United States (Rahman et al., 2016; University of Michigan, 2021).

Life cycle inventory (LCI)

LCA inventory typically uses two types of data: foreground data and background data. Foreground data specific to the modeled system have been collected directly at the Plummer WRRF or provided by the facility operator. Standardized, transparent, and referenced background information is provided by *Ecoinvent 3.7.1* Life Cycle Inventory (LCI) database included in the *SimaPro 9.2.0.2* PhD version software, as well as the DATASMART database with the US-specific processes, consolidated into one library project, the US-EI 2.2 library (LTS, 2020; Wernet et al., 2016).

There is a debate among the researchers on the inclusion of construction within the system boundaries of an LCA. The most recent and comprehensive study on the application of LCA in wastewater studies recommends including construction inventories in wastewater LCA studies (Corominas et al., 2020; Rebello et al., 2021). We used a design life of 20 years for the LCI calculations to allocate the construction burden across the number of functional units provided by the facility (Rahman et al., 2016; Renou et al., 2008; University of Michigan, 2021). A process flow diagram with the actual material and electricity inputs considered within the system boundaries under this LCA is presented in Figure 3.

The City of Plummer owns and operates an electricity distribution system using the power purchased from the Bonneville Power Administration (BPA) (Plummer, 2022). BPA is a nonprofit federal power marketing administration based in the US Pacific Northwest. It delivers electrical power from 31 federal hydroelectric projects in the Northwest, one nonfederal nuclear plant, and several small nonfederal power plants (BPA, 2022). We used the actual BPA energy mix information for 2020 to model the electricity input process in the LCA rather than an estimated regional energy mix (BPA, 2021; LTS, 2020).

Considering that an average flow rate is 806 L/min (213 gal per minute), the system would need 1.24 min to treat 1 m^3 of the influent. The electrical consumption by each device within the system was calculated and is presented in Table 1.

The air compressor consumes 94.3% of the overall energy used in this reactive filtration process. In contrast, the electricity used by the influent water pump was 4.2%, and the main control panel with the two chemical dosing pumps used 1.5%.

Materials used for the main components in the reactive filtration system are presented in Table S1.

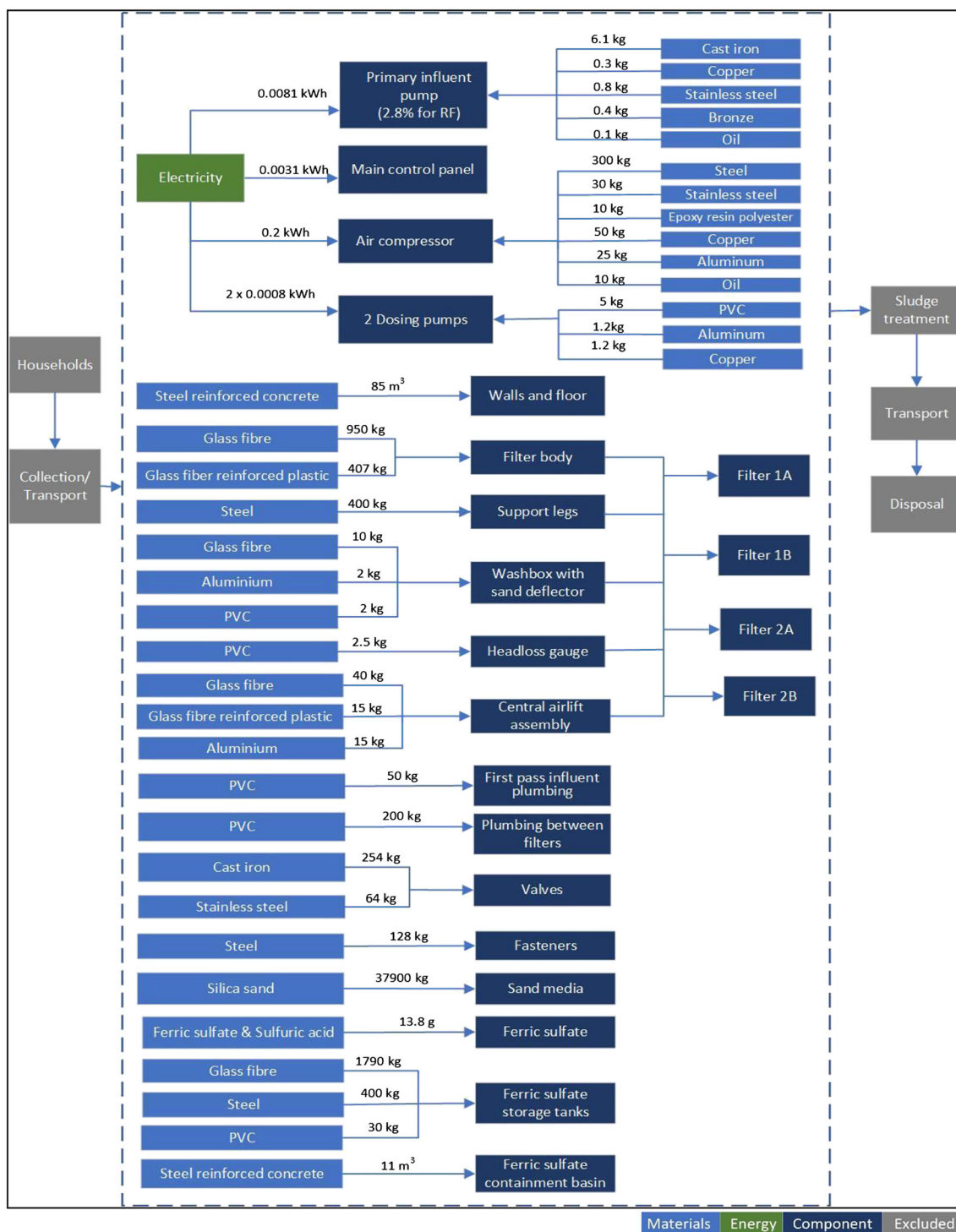


FIGURE 3 Process flow diagram for the Plummer WRRF reactive filtration, where energy and chemical use is per 1 m³ influent

LCIA

We used the ReCiPe midpoint analysis method (hierarchical perspective) for impact assessment calculation with the *SimaPro*® 9.2.0.2 PhD version software (Goedkoop et al., 2009; Huijbregts et al., 2017) and selected the impact categories that are most relevant to the goal and

scope of this study. The full 18 impact categories considered in the ReCiPe are shown in Figure S1.

Considering that the wastewater treatment process mainly involves environmental quality and climate change-related issues (Renou et al., 2008) and that one of the most pressing environmental issues in the region is eutrophication due to excess phosphorus and the warming

TABLE 1 Electricity use by the main system components, per 1 m³ of influent, for the Plummer WRRF

Treatment process component	Voltage	Electrical consumption to treat 1 m ³ (kWh)
Influent pump H4HX1500FC	480	0.008
Ferric sulfate dosing pump 1	120	0.001
Ferric sulfate dosing pump 2	120	0.001
Rotary screw air compressor, 10 HP, 38 cfm	480	0.180
Control panel	120	0.003
Total		0.193

climate, this LCA study targets the following impact categories included in the SimaPro ReCiPe analysis method: GWP (in CO₂e), freshwater eutrophication (FEP), marine eutrophication (MEP), and mineral resource scarcity (MRS). The mandatory phases of impacts assessment (i.e., classification and characterization) defined by the ISO standard were conducted (ISO, 2006b).

Classification is the assignment of LCI results to an impact category, where the inventory components (extractions or emissions from and to the environment) are assigned to the impact categories they may contribute to (Goedkoop et al., 2016). Characterization is the calculation of category indicator results, where LCI results are converted to common units using characterization factors (CF) and aggregated within the same impact category (ISO, 2006b). The CF is determined by the impact assessment method, in this case, the ReCiPe 2016. In other words, characterization describes the scientific tools that link the inventory results to an endpoint area of protection, and the results are expressed as a numerical indicator (Goedkoop et al., 2016).

The midpoint CF for climate change is the GWP, which quantifies the increase of the infrared radiative forcing caused by the emission of 1 kg of GHG. GWP is expressed in kg CO₂ equivalents (CO₂e) released into the atmosphere (IPCC, 2014; Joos et al., 2013).

Phosphorus increase in freshwater is the indicator for freshwater eutrophication impact category. Freshwater eutrophication potential (FEP) is expressed in kg P to freshwater equivalents (Huijbregts et al., 2017). Marine eutrophication is caused by the rise of nutrient levels in riverine and marine systems due to the runoff and leach of plant nutrients such as N and P from soil. In the ReCiPe 2016 LCIA method, it is assumed that nitrogen is the limiting nutrient in marine waters (Cosme et al., 2015).

An indicator of marine eutrophication is the dissolved inorganic nitrogen increase in marine water. MEP is measured in kg N to marine water (Huijbregts et al., 2016).

The impact category indicator for mineral resource scarcity is the increase of ore extracted due to ore grade decrease, which is the concentration of that resource in ores worldwide due to its primary extraction. This, in turn, will increase the amount of ore produced per kilogram of mineral resource extracted. The midpoint CF for mineral resource scarcity is surplus ore potential (SOP), which considers the average future ore production caused by the extraction of a mineral resource and is expressed as kg Cu equivalent (Vieira et al., 2016a; Vieira et al., 2016b).

Life cycle interpretation

Sensitivity analysis for an LCA model in SimaPro involves changing an assumption and recalculating the LCA to see how different assumptions affect the results. For example, switches can be set for different electricity grids or different allocation principles to be used throughout the LCA model. We performed a sensitivity analysis using input parameters to check the model sensitivity to the chemical used for the treatment, for example, ferric sulfate, ferric chloride, ferrous chloride, and aluminum sulfate. Another sensitivity check was conducted for different scenarios related to electricity grid inputs. In addition to the sensitivity analysis, we performed uncertainty analysis with a Monte Carlo simulation technique (Goedkoop et al., 2016).

RESULTS AND DISCUSSION

LCIA

The quantitative results of the life cycle impact analysis of the reactive filtration for each impact category are presented in Table 2. The proportional contribution of each of the major inputs for the GWP, FEP, MEP, and MRS categories is displayed in Figure 4. Process contribution analysis shows that more than 46% of the CO₂e impact comes from the steel-reinforced concrete used in the walls and the floor of the facility containing and supporting the reactive filtration process equipment, as well as in the ferric sulfate containment basin. Concrete is observed to be about 8% of the global carbon footprint (Nature, 2021), and exploring its use in WRRF technologies is useful in addressing the need for climate-resilient construction. In the reactive filtration facility at Plummer

TABLE 2 Impact analysis results at Plummer WRRF per 1 m³ water functional unit

Impact category	Global warming (kg CO ₂ eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)	Mineral resource scarcity (kg Cu eq)
Total	2.01×10^{-2}	1.45×10^{-5}	8.05×10^{-7}	5.85×10^{-4}
Concrete walls and floor	8.49×10^{-3}	3.79×10^{-6}	3.03×10^{-7}	6.94×10^{-5}
Filter 1A	8.44×10^{-4}	2.80×10^{-7}	4.52×10^{-8}	5.65×10^{-6}
Filter 1B	8.44×10^{-4}	2.80×10^{-7}	4.52×10^{-8}	5.65×10^{-6}
Filter 2A	8.44×10^{-4}	2.80×10^{-7}	4.52×10^{-8}	5.65×10^{-6}
Filter 2B	8.44×10^{-4}	2.80×10^{-7}	4.52×10^{-8}	5.65×10^{-6}
Fasteners	1.02×10^{-4}	3.52×10^{-8}	5.10×10^{-9}	8.74×10^{-6}
Ferric sulfate	4.16×10^{-3}	2.23×10^{-6}	1.53×10^{-7}	3.66×10^{-4}
Ferric sulfate storage tanks	7.8×10^{-4}	2.23×10^{-7}	2.8×10^{-8}	7.32×10^{-6}
Ferric sulfate containment basin	8.49×10^{-4}	3.79×10^{-7}	3.03×10^{-8}	6.94×10^{-6}
Air compressor	1.43×10^{-3}	5.83×10^{-7}	6.54×10^{-8}	7.54×10^{-5}
Dosing pump 1	8.39×10^{-6}	4.94×10^{-9}	3.38×10^{-10}	4.09×10^{-7}
Dosing pump 2	8.39×10^{-6}	4.94×10^{-9}	3.38×10^{-10}	4.09×10^{-7}
First pass influent plumbing	1.75×10^{-5}	5.69×10^{-9}	7.44×10^{-10}	5.67×10^{-8}
Main control panel	4.63×10^{-4}	9.84×10^{-7}	2.47×10^{-8}	1.77×10^{-5}
Sand media	2.11×10^{-4}	3.75×10^{-8}	2.65×10^{-9}	2.59×10^{-7}
Plumbing between filters	7.01×10^{-5}	2.28×10^{-8}	2.98×10^{-9}	2.27×10^{-7}
Valves	1.05×10^{-4}	3.83×10^{-8}	4.39×10^{-9}	6.15×10^{-6}
Primary influent pump	6.86×10^{-5}	3.17×10^{-8}	3.15×10^{-9}	3.65×10^{-6}
Effluent phosphorus	0.00	5.00×10^{-6}	0.00	0.00

WRRF, concrete is also the largest contributor to the marine eutrophication impact category (39.1%). The second largest contributor (20.7%) in the GWP category is the ferric sulfate used in (re)generation of the HFO-coated sand in the tertiary RF treatment. It is also the largest contributor to the mineral resource scarcity impact category (62.5%). Thirty-five percent of the FEP is attributed to effluent phosphorus. The reactive filtration technology makes up 15.4% of the FEP coming from the ferric sulfate and about 26.2% from the concrete. The large contribution from the ferric sulfate prompts further exploration of impacts from alternatives for the chemical inputs.

The LCA contribution analysis shows about a third of the relative impact in the FEP from the Plummer facility's nominal at or below detection-limit process effluent total phosphorus, with the remainder arising from pollution associated with the manufactured components,

construction concrete, and operational inputs of the process. Because FEP calculated from an LCA is a global impact, it is challenging to apply the analysis outcome of a specific WRRF to its surrounding watershed, even if a third of the FEP contribution is local. In this case, the overall residual FEP impact for 1 m³ at 1.45×10^{-5} kg P equivalent (0.0145 mg/L) is *de minimis* in comparison with an FEP alternative scenario that allows for direct secondary TP discharge without tertiary reactive filtration that is nominally $1-2 \times 10^{-3}$ kg P equivalent for 1 m³ (1-2 mg/L). The comparison indicates that reactive filtration in this case study reduces FEP by 99% compared with the influent levels coming from the secondary clarifier if allowed to directly discharge. This result significantly exceeds the 85% FEP impact reduction limit for advanced nutrient removal technology predicted by Rahman et al. (2016). Although it is beyond the scope of the present work, this result presents the utility of applying LCA

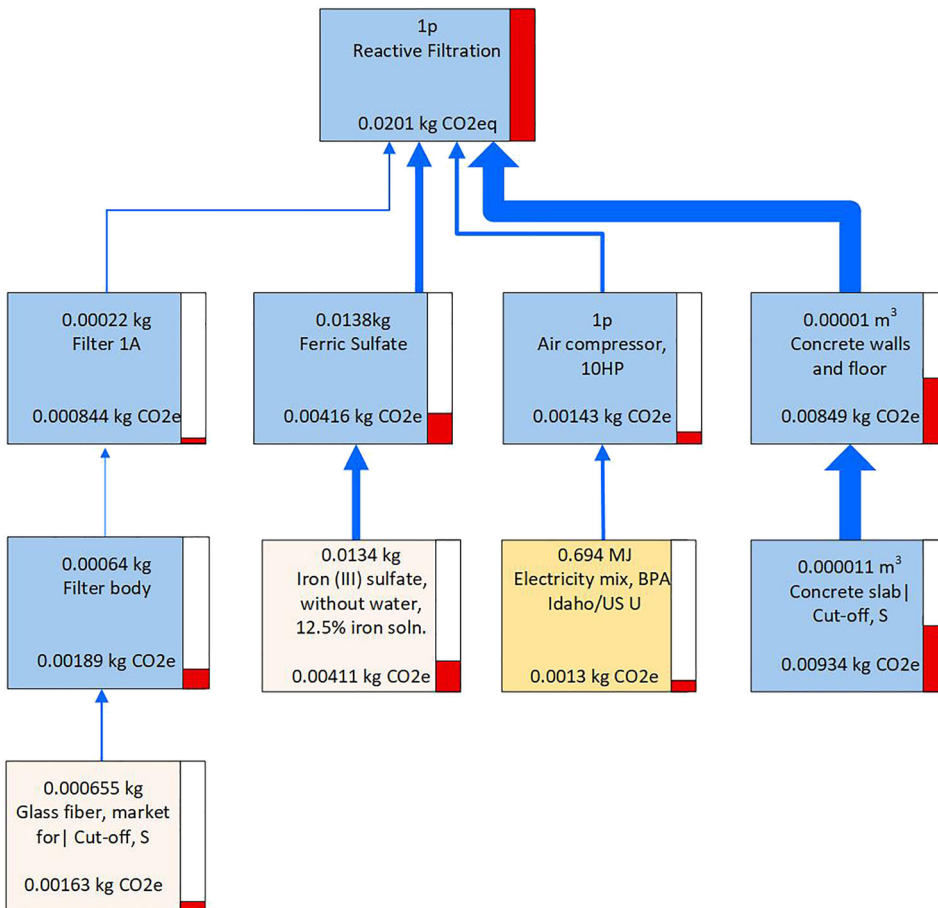
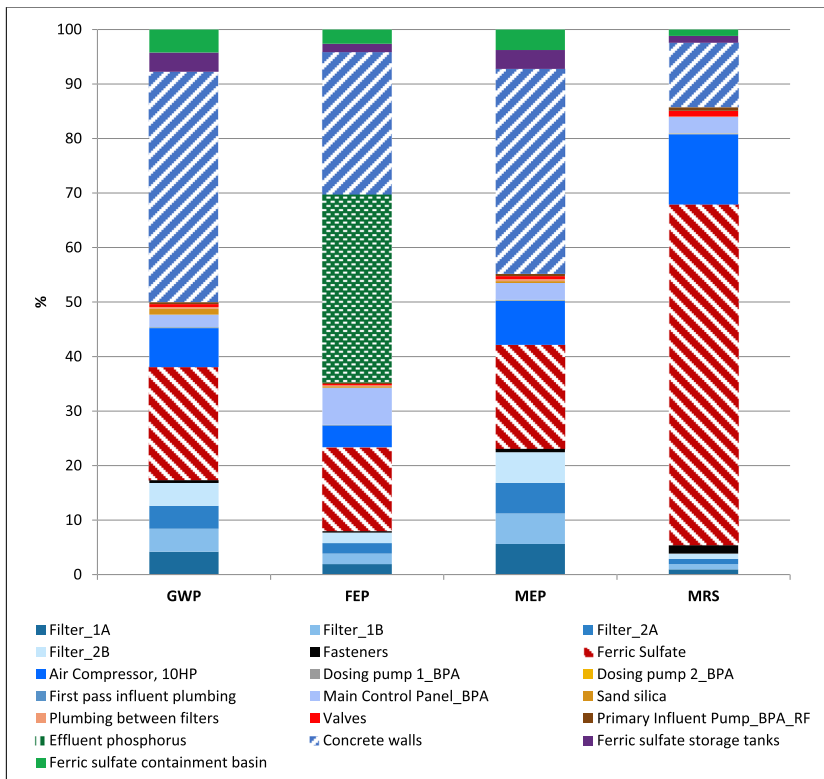


FIGURE 5 The GWP network diagram of the major contributing elements (>4.4% contribution) for dual reactive filtration at Plummer WRRF shows 0.02 kg CO₂e impact per 1 m³ of treated water. The results show the unit contribution in the number of pieces (1 p = 1 piece), mass, volume, or energy. The bottom number in each unit box is the carbon dioxide equivalent contribution, with a corresponding red thermometer bar indicating relative contribution.

impact analysis as an additional resource in developing technology-based effluent limits that satisfy water quality needs, balancing the permit's targeted watershed without contributing to global pollutant generation and release (USEPA, 2022b).

The LCA network analysis shows that the steel-reinforced concrete used for the floor and the walls of the reactive filtration facility housing the equipment at the Plummer WRRF have a significant impact on the GWP at 0.0085 kg CO₂e (Figure 5). This GWP network analysis shows the second and third large contributors are the Fe₂(SO₄)₃ and the BPA electricity mix for the air compressor with 0.0041 kg CO₂ eq and 0.0013 kg CO₂e, respectively, of the carbon equivalent footprint.

There are some studies on innovative “green” cements that are used to produce low-carbon concrete. Novel cement materials that could replace conventional Portland cement have up to 50% lower CO₂ emissions (Lehne & Preston, 2018; Maddalena et al., 2018; Naqi & Jang, 2019; Vizcaíno-Andrés et al., 2015). To reduce the large CO₂e impact from concrete, similar facilities may adopt green cement construction alternatives as these become more widely available.

Choice of metal salts used with sand filtration

To analyze the impacts of the metal salt type used in the RF treatment process, alternative salts were input as replacements for the ferric sulfate, assuming a mass equivalent dose. We compared the baseline, actual reactive filtration at Plummer using ferric sulfate Fe₂(SO₄)₃ reagent concentration with replacements ferric chloride FeCl₃, aluminum sulfate Al₂(SO₄)₃ (alum), and polyaluminum chloride Al₂Cl(OH)₅ (Figure 6). Aluminum salts

are not used in the formalized reactive filtration process (Newcombe, Rule, et al., 2008; Newcombe, Strawn, et al., 2008); however, they are commonly used in water treatment and thus useful for comparison.

The results show that compared in equal mass with the iron salts, aluminum salts have a larger environmental footprint in all four impact categories discussed, apart from ferric chloride having about a 13.7% larger impact than aluminum sulfate in the marine eutrophication impact category. Ferric sulfate has the lowest impact on GWP, with 10.1% lower than ferric chloride, 26% lower than alum, and half as much as polyaluminum chloride. Iron sulfate is the best option in terms of the FEP and MEP impact categories; however, ferric chloride has the lowest impact in the MRS category, with about 50% lower impact compared with the baseline ferric sulfate. In the mineral resource scarcity impact category, alum has about 28% larger contribution than ferric sulfate. Polyaluminum chloride demonstrates the highest environmental impact in all four impact categories.

Increased raw material prices and depletion of natural aluminum and iron resources are driving the wastewater coagulant manufacturers to use alternative raw materials (ARMs) that originate from waste or industrial by-products. The two primary ARMs used to produce iron salt-based coagulants are ferrous sulfate (a by-product from the manufacturing of titanium dioxide) and ferrous chloride (by-product/wastes in the steel industry). Sodium aluminates and aluminum sulfates from the aluminum industry are also used as ARMs in the coagulant industry (Shestakova & Hansen, 2020). Aluminum sulfate is a widely used coagulant; hence, these impact analysis results, including significant CO₂e footprint differences, may be helpful to wastewater treatment operators in exploring metal salt process alternatives for climate resilience.

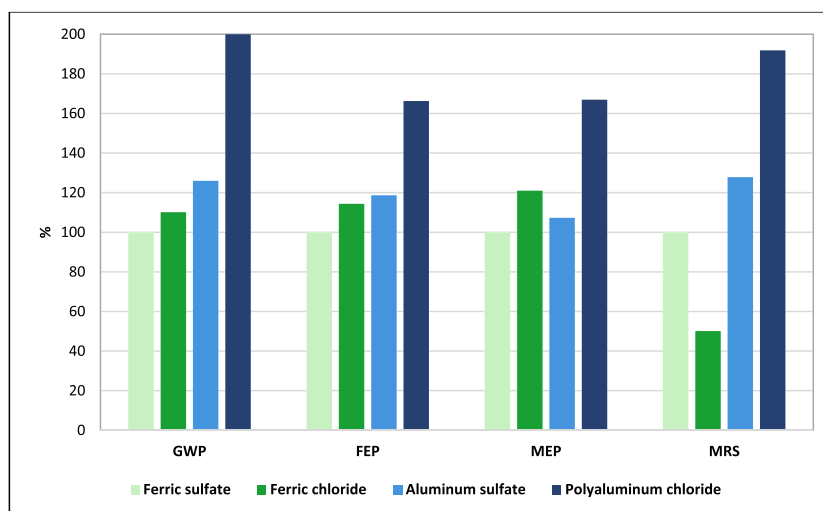


FIGURE 6 Comparative “what if” analysis of LCA impacts at Plummer WRRF with different metal salt chemicals used in related water treatment processes

Comparative analysis of energy input mixes

The grid energy for the City of Plummer is predominantly hydropower produced and delivered in the US Northwest region by the BPA. However, if this WRRF were located elsewhere, with a less “renewable” grid mix, environmental impact contribution amounts would likely shift. Hence, we conducted a contribution analysis for the scenario with the US Northeast Power Coordinating Council (NPCC) US-only data for medium voltage electricity from the *Ecoinvent* database (Wernet et al., 2016) (Figure 7).

The results indicate that the largest environmental load is associated with the air compressor, with 67.8% in the GWP and 60.7% in the MEP impact categories. Mineral resource scarcity impact is dominated by ferric sulfate, reaching 60%. The share of the effluent TP in the FEP in this configuration is 28%, followed by concrete infrastructure and the air compressor, at 21% each.

The overall environmental footprint differences between the existing configuration with the BPA energy and the US national grid are explored in detail below,

indicating that the energy input source is a crucial factor shaping the GWP. The BPA energy used in the reactive filtration at Plummer, Idaho, has three times lower GWP compared with the same technology if it was in an area with an energy supply from the NPCC grid mix. Likewise, FEP is lower by 22%, MEP is 2.4 times lower, and MRS is lower by 4.1%.

Air compressor optimization

During the on-site data collection, we noted that the air pressure delivered to the central airlifts in the continuous upflow, moving bed sand filters was significantly higher than required for the optimal filter performance. As shown in Figure 7, electricity consumption by the air compressor has a major impact on all impact categories. Thermodynamic calculations for isentropic energy requirements indicate that reducing the pressure by half, from 862 (125 psi) to 431 kPa (62.5 psi), would enable saving of 32% of its energy use while still maintaining pressure needed for pneumatic valves elsewhere at the facility (Mckane, 2003) (analysis available in Table S3).

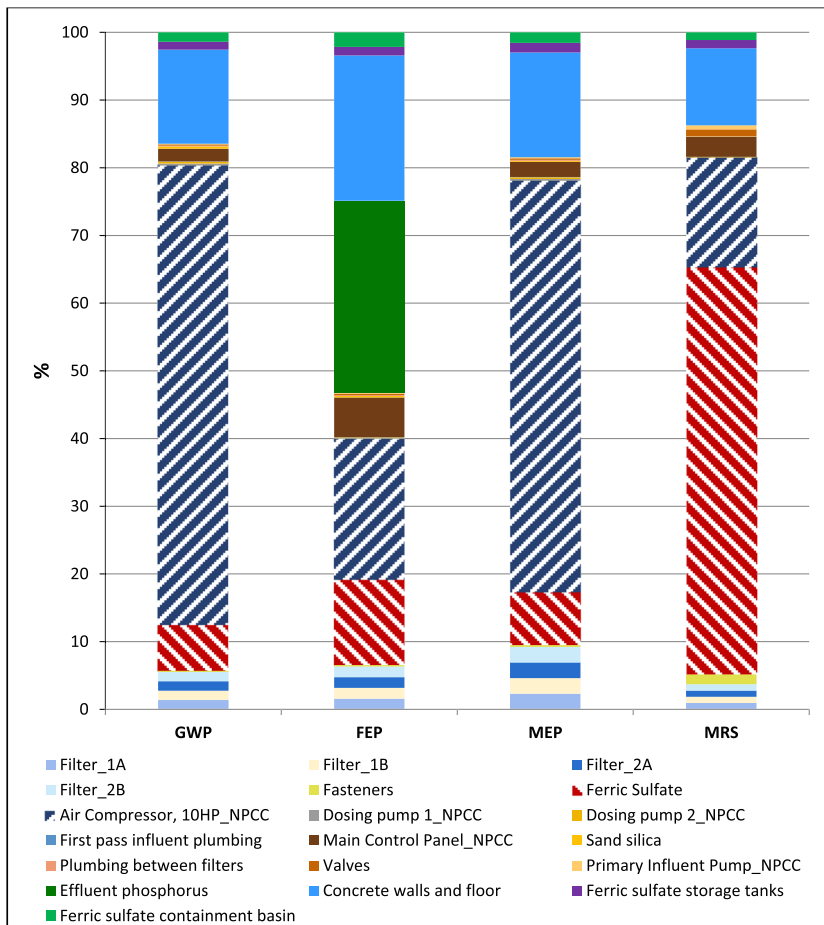


FIGURE 7 Contribution analysis of the “what if” scenario for Plummer WRRF reactive filtration using the NPCC US energy mix

We also used the US Department of Energy's MEASUR tool to calculate compressed air energy savings (USDOE, 2022), which agrees with this estimation. There are additional ways to improve compressor energy efficiency, such as ducting cooler outside air to improve heat exchange, but in this analysis, only pressure reduction was considered.

With the current configuration of the BPA energy mix, compressor optimization can reduce environmental footprint by 0.6%–3.1% through different impact categories, whereas, in the case of the national grid mix, such optimization would reduce the GWP by 21.6%, FEP by 6.1%, the MEP by 19.1%, and the MRS by 4.3% (Figure 8). The International Energy Association estimates that 80% of global carbon emissions arise from energy use (IEA, 2021); thus, energy efficiency is a critical factor in addressing climate change.

Comparative LCA analysis of renewable energy scenarios

GWP can be further reduced by switching to solar or wind energy. To test this in *SimaPro*, we built “what if” scenarios for the existing reactive filtration by replacing the electricity inputs in the system with modified grid mixes in DATASMART electricity mix energy processes (LTS, 2020), assuming a 100% photovoltaic or a 100% wind energy in the grid mix, respectively. A comparative analysis of four energy options is presented in Figure 9, including the Plummer RF with BPA energy and the solar, wind, and NPCC grid for the United States. This analysis allows further exploration of the CO₂e GWP, and the LCA results show a more than 3× impact increase.

A comparative LCIA calculation indicates that the existing BPA energy has the lowest environmental

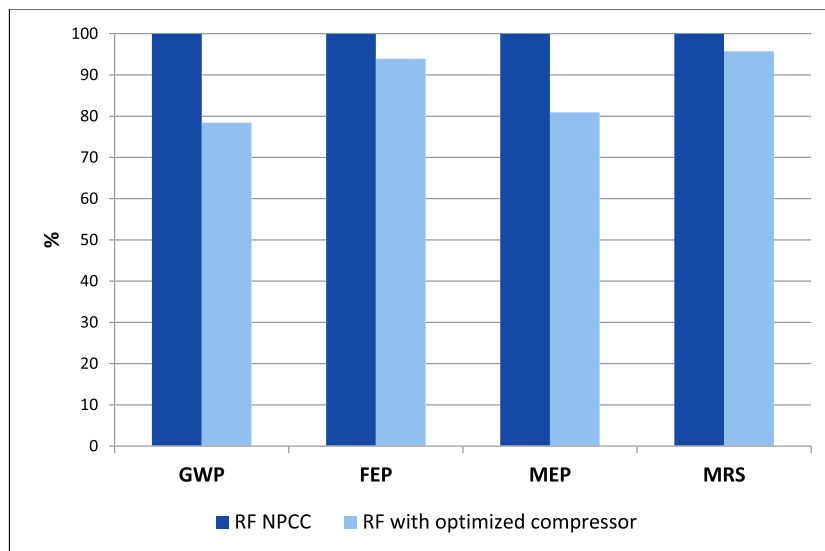


FIGURE 8 Comparative analysis of the Plummer WRRF reactive filtration with NPCC US energy input and optimized air compressor

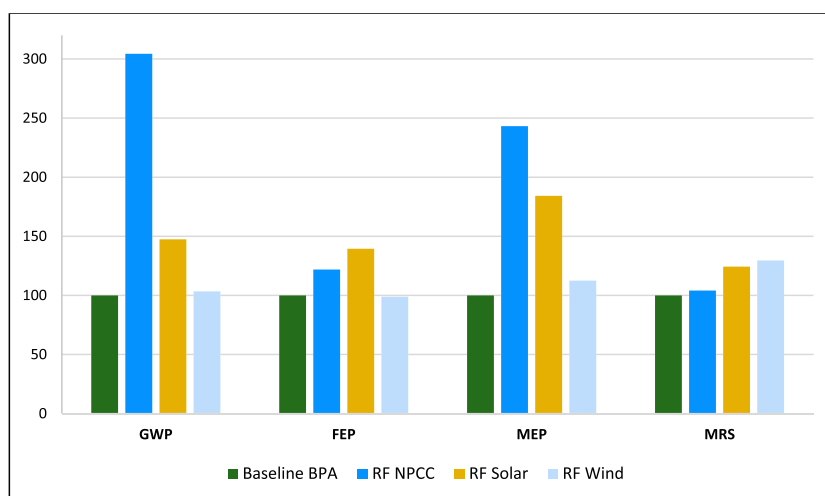


FIGURE 9 Comparison of the Plummer WRRF reactive filtration site with different energy mix options

footprint due to its hydropower origin. However, if the WRRF was located elsewhere with an NPCC grid mix, switching to the solar option would help to reduce the GWP by half, but the freshwater eutrophication and mineral resource scarcity show a 17.6% and 20.3% increase, respectively. Electricity production with grid-connected photovoltaic power plants has additional impacts from the materials, chemicals, and energy used to produce photovoltaic energy. Input processes include the production mix of photovoltaic electricity in the country, assumptions for the share of different technologies, the amount of solar energy transformed into electricity, and waste heat emission due to losses of electricity in the system (LTS, 2020).

Compared with the NPCC grid and the solar option, wind energy has a significantly lower environmental footprint in three out of four impact categories but has the largest load in MRS impact category. The latter may be due to material consumption for the main parts of the wind turbines, such as the fundament, tower, and nacelle (Jungbluth et al., 2005; Schreiber et al., 2019), as electricity production at wind power plants includes the modules for the wind power plant 800 kW and the wind power plant 2 MW, using modified Ecoinvent 2.2 data updated with the US energy (LTS, 2020). Hence, the decisions on any technology modifications should be made with consideration and weighing of the priority goals in terms of the environmental impact category of concern.

CONCLUSIONS

Reactive filtration LCA results for the Plummer WRRF show that the GWP per 1 m³ of treated water with the TP removal to about 0.005 mg/L is 0.02 kg CO₂e, with 46.5% of this impact coming from concrete in the construction of supporting facility floors and walls. Although lack of approach standardization makes LCA impact comparisons challenging, the results of this study are favorable when compared with the carbon footprint findings of previous work focused on TP removal.

The global warming impact category is the most widely reported in published wastewater treatment LCA studies. Niero et al. (2014) find a GWP of multiple unit operation WRRFs using chemical precipitation and advanced biological treatment removing phosphorus down to 0.5 and 0.3 mg/L, respectively, in the range of 0.195–0.213 kg CO₂e per 1 m³ of influent wastewater. In contrast, LCA results for sedimentation with membrane filtration tertiary treatment, removing TP down to 0.01 mg/L, report GWP in the range of 1.32–1.42 kg CO₂e per 1 m³ (Rahman et al., 2016).

Comparative LCA of chemicals used in water treatment shows that iron sulfate is the best option in terms of the GWP, freshwater eutrophication, and marine eutrophication impacts. Ferric chloride, however, has the lowest impact in the mineral resource scarcity category, and polyaluminum chloride shows the largest footprint in all four impact categories.

LCA of “what if” scenarios with renewable energy options shows that hydropower has a smaller environmental footprint compared with solar and wind alternatives in this installation. Knowledge of trade-offs between various impact categories will help in making sustainability-oriented decisions considering the priority impact areas in the future. In this present case, the use of renewable hydropower energy isolates construction concrete as a target for reducing CO₂e footprint.

Long-term goals for environmental sustainability incorporate reducing the use of natural resources. In the 21st century, wastewater treatment systems are shifting from the pollutant removal paradigm to one that includes resource recovery, such as phosphorus (Guest et al., 2009). Whereas P is a critical element for life, minable fossil phosphorus reserves are being depleted globally (Reijnders, 2014). Hence, phosphorus removal and recovery in WRRFs represents an opportunity for increased resource recovery and reuse for food security while at the same time minimizing CO₂e footprint to mitigate climate change.

Phosphorus removal and recovery from wastewater is an active area of research. Current work shows this task can be accomplished with a variety of engineered and waste materials, and the efficiency of these processes highly depends on the material used. For example, metal (e.g., Al, Ca, Ce, Fe, La, Mg, Mn, Zn, and Zr) hydroxides/oxides and selected engineered adsorption media show promise (Bacelo et al., 2020). Bio-derived materials and industrial wastes may also serve as phosphate adsorbents (Zhou et al., 2022). Addressing the multiple societal challenges of clean water, food security and carbon sequestration needed to mitigate climate change, biochar has had considerable attention in phosphate removal and recovery from water (Almanassra et al., 2021; Möller & Strawn, 2019). Further study on a novel extension of this reactive filtration system called “biochar water treatment” is ongoing and will be presented in future work.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this paper are openly available from the University of Idaho Institutional Repository at <https://doi.org/10.7923/QGMB-HT58>.

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SUPPORTING INFORMATION

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