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Carbon Footprint and Sensitive Design Parameters of Residential and Industrial (Whey) Wastewater Treatment Plants: A Comparative Life Cycle Assessment (LCA)

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Abstract

This study calculates the carbon footprint of chemical coagulants and operational energy for residential and industrial (whey digestion) wastewater treatment using ReCiPe 2016 methodology within a clearly defined system boundary from cradle to gate. Data from water treatment facilities have been analyzed to quantify environmental impacts and identify sensitive design parameters. The estimated emission of treating 1 m^3 of wastewater from whey digestion (7.1195 kg CO_2 eq) is over 50 times higher than that of a residential one (0.1349 kg CO_2 eq). Life cycle impact assessment (LCIA) reveals that iron (III) chloride (40% in H_2O) and operational electricity consumption have higher impact categories compared to other design components. The uncertainty analysis indicates that electricity consumption (r = 0.4) is the dominant contributor to emissions, with a mean value of 4.22 kg CO_2-eq per m^3 of wastewater treated. In contrast, iron (III) chloride emerges as the most sensitive parameter (r = 0.88) with small variations in dosing causing a disproportionately large impact on overall emissions. Therefore, the optimized use of an iron-based coagulant, the adoption of membrane electrolysis, and the integration of renewable electricity into the process supply chains have been identified as effective strategies for reducing emissions.

Keywords: wastewater treatment; life cycle assessment (LCA); chemical coagulants; sensitivity analysis

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1. Introduction

Wastewater treatment plants are essential infrastructure for mitigating environmental pollution; however, anthropogenic greenhouse gas (GHG) emissions are associated with both direct electricity consumption and indirect emissions related to the production and transportation of chemical disinfectants [1]. Therefore, details on chemical disinfectants and energy consumption are fundamental to assessing the quantitative impacts. A proper life cycle inventory (LCI) establishes the link between wastewater treatment operation and

associated upstream environmental burdens [2]. Information on chemical inventories and operational energy consumption is required to estimate the carbon footprint and associated uncertainties in the life-cycle assessment (LCA) [3].

Environmental impacts of a wastewater treatment plant consist of two main components: (1) direct wastewater treatment using coagulation and flocculation and (2) sludge management using incineration. Chemical coagulants play a significant role in removing suspended solids, phosphorus, and other colloidal contaminants during wastewater treatment [4]. Contaminants in residential wastewater primarily consist of fine particulates, natural organic matter, and phosphate compounds [5,6]. In contrast, whey-based industrial wastewater is characterized by high concentrations of proteins, lactose, fats, and dissolved organic carbon [7]. Hence, whey digestion is a representative of high-strength effluent commonly encountered in dairy food processing centers rather than an outlier [8,9]. This higher concentration of pollutants increases turbidity and chemical oxygen demand (COD), which requires higher coagulant dosages and more intensive treatment [10,11]. Iron (III) chloride ($FeCl_3$), iron sulphate ($Fe_2(SO_4)_3$) or $FeSO_4$, and aluminium sulphate ($Al_2(SO_4)_3$) are three main chemical disinfectants that neutralize the electrical charge of fine particles, destabilize them, and cause them to coagulate [12].

These metal salts undergo rapid hydrolysis at the water contact and form metal hydroxide precipitates [13]. Protein- and phosphate-enriched whey-based wastewater appears to be effective through this ferric hydroxide surface mechanism [14]. The hydrolysis reaction destabilizes colloidal particles and promotes floc formation. For example, $FeCl_3$ forms ferric hydroxide ($Fe(OH)_3$) as a flocculant to adsorb suspended solids, organic matter, and phosphorus, as shown in Equation (1). Similarly, iron sulphate contributes to charge neutralization and floc growth, as shown in Equation (2). Additionally, sulphate influences alkalinity and buffering capacity in residential wastewater treatment with lower organic loading. Aluminium sulphate (alum) forms aluminium hydroxide to remove turbidity and phosphorus contents from wastewater, as shown in Equation (3). However, alum's sensitivity to pH requires careful consideration of the alum dosage for treating effluent [15]. Higher organic load and protein levels in whey-based wastewater increase demand for metal-specific coagulants. Additionally, hydroxide precipitates encapsulate dissolved organic compounds. Quantities of these chemical coagulants are maintained to achieve the regulatory effluent standards. Energy-intensive processing of these chemicals, including mining, refining, and chemical synthesis. The conversion of iron ore or bauxite requires proper extraction, high temperatures, and other processes, all of which result in greenhouse gas emissions [16]. Natural plant-based coagulants such as roselle seeds, cactus, moringa oleifera, chitosan, hyacinth bean, and others have been used in several studies to assess their efficiency [17,18]. These have performed well in removing turbidity and organic pollutants. However, disinfection aspects of adopting biobased coagulants need further exploration.

$$FeCl_3 + 3H_2O = Fe(OH)_3 + 3H^+ + 3Cl^- \quad (1)$$

$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4 \quad (2)$$

$$Al_2(SO_4)_3 + 6H_2O = 2Al(OH)_3 + 3H_2SO_4 \quad (3)$$

Wastewater sludge incineration has also been considered alongside direct treatment processes to compare their environmental impacts. Incineration of sludge has been adopted at these water treatment plants due to high pollutant loads and limited disposal options [19,20]. Sludge incineration in the consequence process reduces the volume and destroys organic contaminants. Natural gas is primarily used to dry and incinerate wastewater sludge. Sludge with a relatively higher moisture content increases demand for natural gas and results in higher emissions. Acidic gases such as hydrogen chloride and sulphur

dioxide are produced in this combustion by the reaction of chlorine and sulphur-containing compounds. Alkaline reagent sodium hydroxide (NaOH) neutralizes acidic gases, while quicklime (CaO) captures and stabilizes them in flue-gas treatment systems, as shown in Equations (4)–(7) [21,22]. Hydrochloric acid (HCl) is commonly used for pH control and chemical cleaning [23]. Nitrogen-rich organic compounds in wastewater sludge are converted to nitrogen oxides, which are controlled by ammonia through the conversion to nitrogen and water, as shown in Equation (8) [24]. The comparative analysis will emphasize the phases to be considered for identifying a reduction strategy.

$$NaOH + HCl = NaCl + H_2O \quad (4)$$

$$2NaOH + SO_2 = Na_2SO_3 + H_2O \quad (5)$$

$$CaO + 2HCl = CaCl_2 + H_2O \quad (6)$$

$$CaO + SO_2 = CaSO_3 \quad (7)$$

$$4NH_3 + 4NO + O_2 = 4N_2 + 6H_2O \quad (8)$$

Electricity is consumed in wastewater treatment for operational processes, such as aeration, pumping, mixing, and advanced nutrient removal [25]. Aeration in the wastewater treatment process typically accounts for the majority of electricity consumption [26]. Electricity on the Australian national grid mainly (64%) comes from fossil fuels, including coal (45%), natural gas (17%), and oil (2%). Whereas renewable sources contribute 36% of total electricity generation, including solar (18%), wind (12%), and hydro (5%) [27,28]. Burning fossil fuels directly produces CO_2 emissions, which contribute to the system's carbon footprint. High-density industrial wastewater, such as from whey digestion, typically requires more intensive aeration and process control than residential wastewater, which significantly increases electricity-related emissions [9]. Hence, the assessed impact on the Australian grid can be further extended to other regions by recalculating the grid composition.

In addition to chemical production and electricity consumption, transporting processed chemicals to the treatment plant also contributes indirectly to the carbon footprint. A distance- and mass-based logistics assumption has been adopted for the relevant wastewater treatment facilities in Queensland, Australia. The combustion of diesel in trucks is part of the upstream process that contributes to transportation-related emissions [29]. Although, small quantities of chemicals are used to treat larger proportions of wastewater, resulting in lower impacts. However, research on coagulation–flocculation processes determines the selection and dosage of coagulants that affect the performance of wastewater treatment plants [30]. Therefore, transportation-related emissions can significantly impact the overall assessment, where higher dosages of chemicals are required for industrial wastewater treatment [31].

This study aims to calculate the carbon footprint of the design components in direct wastewater treatment facilities, including iron (III) chloride, iron sulphate, and aluminium sulphate, as well as electricity consumption and transportation. Omitting these classified elements will underestimate the measurement of CO_2 emission potential and reduce the validity of the results. Comparative analysis reveals that variations in organic load and nutrient levels in industrial (whey digestion) wastewater result in additional energy and coagulant demand and, ultimately, greater impacts in the impact categories than in residential ones. The existing literature presents point-specific deterministic carbon footprints rather than accounting for the relative uncertainties of design parameters and operational variables [1,32,33]. This study performs a sensitivity analysis alongside life cycle assessment (LCA) to show variations in emissions resulting from coagulant doses and operational energy consumption. By explicitly integrating uncertainty analysis into

the LCA model, it moves beyond specific calculation to identify the most contributing and sensitive parameters for consideration. The novelty of this research lies in conducting uncertainty analysis within LCA frameworks to provide a basis for decision-making and to address critical factors for reducing emissions.

2. Materials and Methods

This study compares the associated carbon footprint for two treatment scenarios by conducting a comprehensive LCA with uncertainty analysis, as shown in Figure 1. The methodological framework differs from other studies by going beyond point-static LCA, integrating probabilistic uncertainty and sensitive design parameters [1,2,34]. The framework quantifies both contributions and variability to identify influential parameters and reports aggregate impacts.

Residential and industrial (whey digestion) wastewater design components are modelled using SimaPro 9.4 and @RISK 8, the Palisade decision tool [35,36]. These design components have been converted into meaningful eighteen (18) environmental impact categories following the ReCiPe 2016 midpoint life cycle assessment methodology [37]. These indicators are climate change, terrestrial acidification, freshwater and marine eutrophication, human toxicity, ecotoxicity, particulate matter formation, photochemical oxidant formation, fossil depletion, metal depletion, water depletion, and others. These indicators reflect the dominant source of emissions and resources associated with design components. In addition to indicators, this study applies statistical-based uncertainty analysis to identify the influential design parameters. The probabilistic distribution of carbon footprint for these two treatment processes is obtained using a pedigree matrix, and the results are expressed as means, standard deviations, confidence intervals, Pearson's correlation coefficients, and rank correlation coefficients [38]. Identification of influential parameters is feasible by justifying these environmental and statistical indicators.

2.1. Characterization of This Study

This study begins by characterizing the wastewater treatment systems used in residential and semi-industrial (whey digestion) facilities. The primary objective of this study is to calculate the carbon footprint and other impacts from direct wastewater treatment. It focuses on how variations in design parameters influence emission patterns. A relatively lower amount of chemical and energy inputs is applied in these conventional residential treatment processes. On the contrary, industrial wastewater from food processing contains a highly concentrated organic load with significant suspended solids and nutrient concentrations [39]. Consequently, significantly higher chemical dosages and greater electricity consumption are required to meet water quality standards from this treatment process.

2.2. Goal and Scope Definition

The goal and scope of this LCA were to elucidate the use of chemicals, the operational energy required, and the transportation involved for treating domestic (residential) and industrial wastewater (whey digestion) within a classified wastewater treatment plant in Australia. Two distinct municipal wastewater treatment facilities in Australia were selected as representative data for this assessment, with operational data from 2024. A moderately large treatment plant (capacity class 2) for treating sewage from residential areas with an average capacity of 71,100 population capita equivalents (PCE) was considered a residential one. Characteristics of per liter residential wastewater were observed with BOD_5 (200–300 mg), COD (400–800 mg), total suspended solids (200–350 mg), nitrogen (30–50 mg), and phosphorus (6–12 mg). A smaller municipal treatment plant associated with whey digestion (capacity class 4), with an average of 5320 PCE, was represented as

a semi-industrial facility typical of the food-processing industry. In the case of per-liter whey digestion, it varies with BOD_5 (20,000–50,000 mg), COD (5000–50,000 mg), total suspended solids (4000–12,000 mg), nitrogen (500–1500 mg), and phosphorus (50–300 mg). The effluent characteristics of whey-based operations related to dairy products differ substantially from those of conventional residential ones [40,41]. Site-specific data may vary, but data collected from treatment facilities provide a basis for assessing environmental impacts and identifying sensitive parameters through LCA-framed sensitivity analysis.

Functional Unit and System Boundary

Chemical use, electricity consumption, and transport activities were quantified across two treatment plants to assess differences in environmental impacts resulting from treatment intensity. The functional unit of 1 cubic meter (1 m^3) of wastewater treatment was chosen to reflect operational practice and the relevant environmental burden from real-world scenarios. Inherent characteristics of the effluents were intentionally preserved in the life-cycle inventory by accounting for higher chemical demand, greater energy consumption, and greater process variability [42]. The distances from the regional distributor of chemical coagulants to residential and whee digestion were 11 km and 25 km, respectively. The amount of wastewater treated from these two classified facilities was 14,220 m^3 (residential class 2) and 1064 m^3 (whey digestion class 4). All design materials and energy consumption were standardized within this functional unit to ensure compatibility between the two wastewater treatment systems, as shown in Table 1.

Table 1. Design components for one cubic meter (1 m^3) of direct wastewater treatment.

Design Components of the Treatment Plant (Direct Wastewater Treatment)	Unit	Domestic (Residential)	Industrial (Whey Digestion)
Iron (III) chloride (40% in H_2O), AusSD U	kg	0.016	1.550
Iron sulphate, at the plant, AusSD U	kg	0.012	1.134
Aluminium sulphate, powder, AusSD U	kg	0.003	0.306
Electricity, low voltage, at the grid, AusSD U	kWh	0.206	8.271
Transport, lorry, fleet average, AusSD U	tkm	0.012	0.979

In addition to the direct wastewater treatment plant, the sludge incineration process included several design components. A lower amount of natural gas was required for residential incineration (0.007 MJ) than for whee-based industrial (0.105 MJ) incineration, as shown in Table 2. A higher organic load indicated a greater need for ammonia to control NO_x emissions. Relevant chemicals, sodium hydroxide and quicklime, were also mentioned for acid gas neutralization and ash stabilization in the flue gas treatment system. Hydrochloric acid for equipment cleaning and pH control was very similar for the two treatment processes. These design components showed the treatment of 1 m^3 of wastewater sludge by incineration, given variations in characteristics and associated burdens.

Table 2. Design components for one cubic meter (1 m^3) of wastewater-generated sludge.

Design Components of the Treatment Plant Sludge Incineration Process	Unit	Domestic (Residential)	Industrial (Whey Digestion)
Sodium hydroxide (50% in H_2O), AusSD U	kg	3.52×10^{-4}	1.70×10^{-4}
Quicklime, milled, packed, AusSD U	kg	1.25×10^{-6}	3.08×10^{-5}
Hydrochloric acid (30% in H_2O), AusSD U	kg	3.95×10^{-6}	3.78×10^{-6}
Ammonia liquid, at regional, AusSD U	kg	7.21×10^{-5}	1.08×10^{-3}
Natural gas, burned in furnace, AusSD U	MJ	0.007	0.105

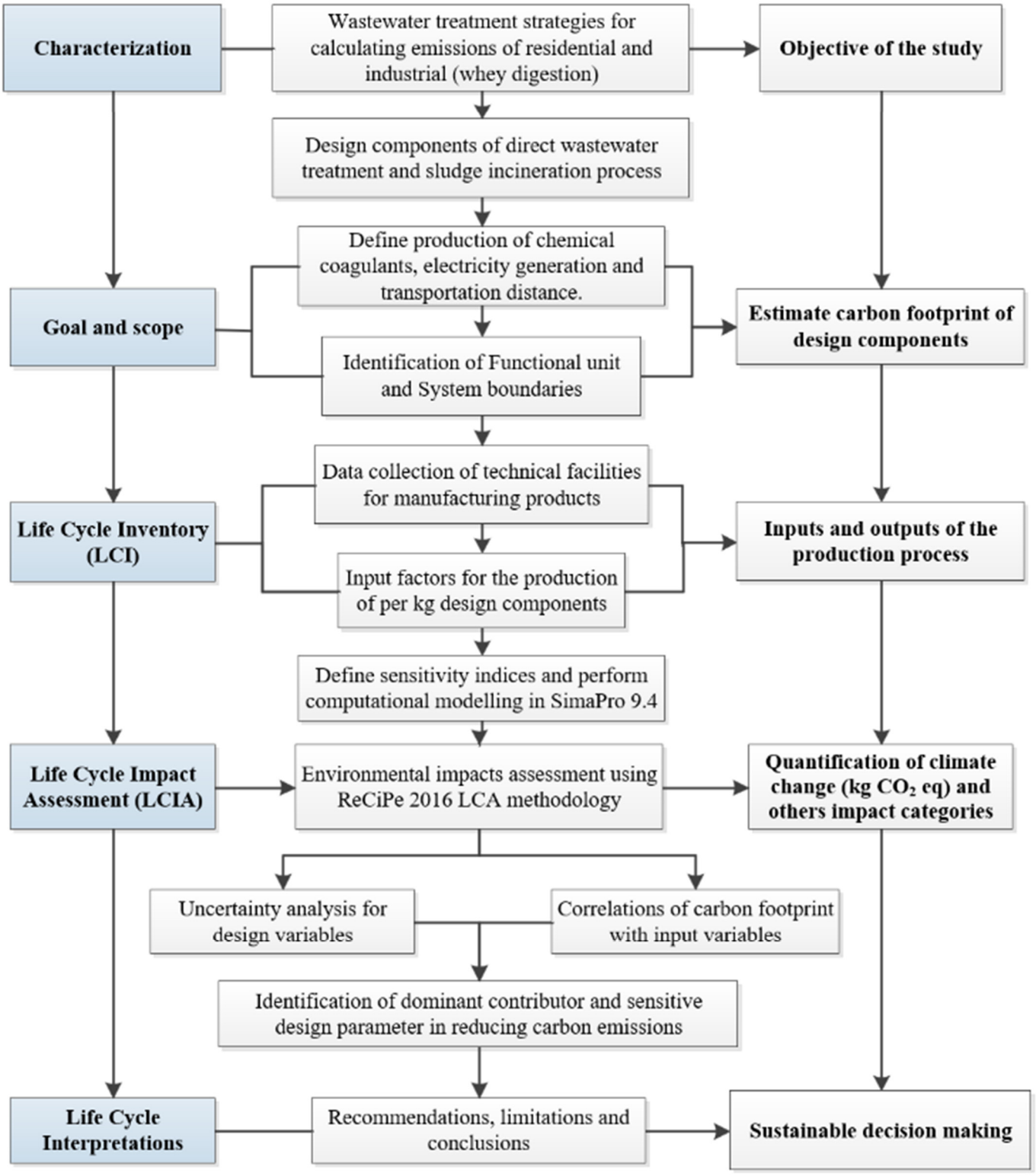

Figure 1. Methodological frame for performing LCA of residential and whey wastewater treatment plants.

The defined system boundary was consistent with a process-based attributional LCA. The LCA focused on the treatment technologies used during the wastewater treatment plant's operational phase. Environmental significance is prioritized for adopted treatment technologies over the entire water treatment facility [43,44]. Sludge incineration is additionally represented to differentiate the magnitude of emissions arising beyond the direct treatment process.

The construction process is capital-intensive, and its associated environmental burdens are amortized over several decades of plant operation. Even in earlier studies, the contribution of infrastructure construction is lower than that of a treatment plant's operational phase [45,46]. Therefore, infrastructure construction and plant maintenance were excluded from this assessment.

The design components of the direct wastewater treatment were modelled in this LCA study as follows:

1. Production of chemical disinfectants for wastewater treatment;
2. Sources of electricity generation and consumption during operation;
3. Transport of chemicals to the wastewater treatment plant.

Infrastructure construction, plant maintenance, sludge handling, and effluent discharge disposal were excluded from the scope, as the objective was to estimate the environmental impact per cubic meter of wastewater treated.

2.3. Life Cycle Inventory (LCI) Development

The Life Cycle Inventory (LCI) data were collected from chemical production facilities, electricity generation facilities, and diesel extraction facilities for transportation. These databases have been adopted in SimaPro 9.4 as the Australian life cycle inventory (AusLCI), compiled from detailed input and output data for the production process, including raw materials extraction, energy consumption, and emissions per kilogram for each design component, as shown in Table 3 [47]. The inventory of iron (III) chloride (40% in H_2O) includes the production process for chlorine using a mercury cell and membrane cell electrolysis and the use of iron scrap, hydrochloric acid, and production facilities, including transportation, water, and electricity consumption. Similarly, iron sulphate includes iron scrap, 40% sulphuric acid in H_2O, electricity consumption, and other components. The production of aluminium sulphate relies particularly on aluminium hydroxide and sulphuric acid as the primary reactants, along with electricity and water consumption.

Table 3. Life Cycle Inventories (LCIs) of wastewater treatment design components.

Known Inputs and Outputs from the Technosphere	Amount	Unit
Iron (III) chloride (40% in H_2O) at the plant (1 kg)		
Chlorine, gaseous, mercury cell at the plant	0.492	kg
Chlorine, gaseous, membrane cell at the plant	0.106	kg
Iron scrap at the plant	0.328	kg
Hydrochloric acid 30% in H_2O at the plant	0.022	kg
Tap water for the user	1.23	kg
Electricity, medium voltage at the grid	0.0186	kWh
Transport, fleet average	0.022	tkm
Facilities, chemical production	0.0169	kg
Iron sulphate at the plant (1 kg)		
Electricity, medium voltage at the grid	0.222	kWh
Iron scrap at the plant	0.212	kg
Sulphuric acid in 40% in H_2O	0.148	kg
Facilities, chemical production	0.00505	kg
Tap water for the user	0.58	kg
Aluminium sulphate powder at the plant (1 kg)		
Aluminium hydroxide at the plant	0.25	kg
Sulphuric acid, liquid at the plant	0.52	kg
Electricity, medium voltage at the grid	0.56	kWh
Tap water for the user	0.28	kg

Table 3. *Cont.*

Known Inputs and Outputs from the Technosphere	Amount	Unit
National Grid electricity generation (1 kWh)		
Electricity, coal at the power plant	0.45	kWh
Electricity, natural gas at the power plant	0.17	kWh
Electricity, oil at the power plant	0.02	kWh
Electricity, solar photovoltaic firm	0.18	kWh
Electricity, hydropower plant	0.05	kWh
Electricity, wind power	0.12	kWh
Electricity, other sources	0.01	kWh
Transmission network, high voltage	8.44×10^{-9}	km
Transmission network, long distance	3.17×10^{-10}	km
Transportation fleet average truck (1 tkm)		
Diesel at the refinery and combustion	0.0221	kg

Note: The background colour and bolded words distinguish the principal design components of the water treatment facilities. Associated inputs in the production system and key process information were included in these inventory datasets below the principal component.

The composition of electricity generation in Australia has been examined separately to assess the impacts of both fossil fuels and renewable sources. This inventory also includes the transmission network to trace emissions from grid losses. Transport-related emissions are generated by diesel fuel production at the refinery and by engine combustion. These inventories are explicitly linked with material, energy, and the systematic flow of upstream industrial production. A transparent representation of the impact assessment has been ensured through the supply chain of the manufacturing process.

2.4. Sensitivity Indices for Design Variables

The sensitivity analysis reveals how the variable design components contribute to the overall system's carbon footprint (kg CO_2 eq) [48]. The pedigree matrix has been adopted to assess uncertainty in individual design components, following the SimaPro 9.4 [49]. Statistical indicators, such as the mean, standard deviation, coefficient of variation, and confidence interval, are used to reflect the six categories in this assessment. These categories are outlined in the ISO 14044 as follows: (1) data reliability, (2) site-specific data, (3) temporal correlations for the operational period of 3–15 years, (4) geographical correlations of relevant data, (5) technological correlations of production data, and (6) relevant uncertainties over fine particle (PM10, PM 2.5) emissions [50,51]. The uncertainties of these variations are calculated by summing up all the identical factors following Equation (9). Sensitivity indices for design components were determined through a Monte Carlo simulation with thousands of iterations based on the selected six (6) criteria of the pedigree matrix [52].

$$\sigma^2 = \sum_{n=1}^{6} \sigma_n^2 \quad (9)$$

A moderate to high level of uncertainty was observed for the chemical coagulants iron chloride (40% in H_2O), iron sulphate, and aluminium sulphate, as indicated by coefficient of variations ranging from 10.5% to 23.8%, as shown in Table 4. As a secondary catalyst coagulant, iron sulphate was the sensitive design component, with a very high CV of 23.8%. However, a wider-ranging confidence interval (1.083–1.935 kg CO_2 eq) for iron chloride 40% in H_2O was identified, clarifying the variations in treatment demand and associated burden with upstream production. Compared to the other two coagulants, aluminium sulphate exhibited a consistent emission profile for its use, as indicated by the mean and CV values of 0.786 and 10.48%, respectively.

Table 4. Sensitivity indices of the wastewater treatment design components.

Design Components	Unit	Emissions Variation in kg CO_2 eq				
		Statistical Indicators			Confidence Intervals	
		Mean	SD	CV	2.5%	97.5%
Iron chloride 40% in H_2O	1 kg	1.436	0.234	16.277	1.083	1.935
Iron sulphate	1 kg	0.294	0.070	23.793	0.201	0.472
Aluminium sulphate	1 kg	0.786	0.082	10.487	0.643	0.970
Australia electricity	1 kWh	0.511	0.020	3.980	0.471	0.551
Transportation	1 tkm	0.105	0.011	10.750	0.087	0.136

Compared to chemicals, electricity consumption exhibited lower sensitivity to emissions, with a smaller coefficient of variation (CV). This indicated uniform data quality (mean, standard deviation = 0.511, 0.020), with a temporal and geographical representation of the Australian grid mix. The relevant contributions of fossil fuel sources from coal (45%), natural gas (17%), and oil (2%) were 0.4171, 0.0764, and 0.0167 kg CO_2 eq consecutively. On the contrary, the contributions from renewable sources (35%) were combined to 0.000487 kg CO_2 eq. Similarly, transportation exhibited moderate uncertainty, with a value of 10.75%, indicating the fleet average dataset used in the LCA. The pedigree matrix indicated that the relevant uncertainties associated with using chemicals in the system were greater than those related to electricity consumption and transportation. Moreover, the relevant uncertainty analysis highlighted that the coagulation was a sensitive parameter compared to other parameters.

3. Life Cycle Impact Assessment (LCIA)

The direct wastewater treatment process has several design components that can lead to emissions, toxicity, and the release of heavy metals and other pollutants. This study evaluated the environmental impacts of the design components using the latest Life Cycle Impact Assessment (LCIA) methodology, ReCiPe 2016 [27,53]. This method was selected due to its alignment with ISO 14040/44-harmonized LCA modelling and compatibility with uncertainty and sensitivity analysis [54]. Midpoint impact categories were assessed in this study to identify specific design parameters contributing to the diversified levels, rather than aggregating impacts to the endpoint damage. Similar trends have been observed in other relevant studies of wastewater treatment plants, where electricity contributes significantly more than other sources [55–57]. This study extends existing research by considering the uncertainty of design parameters, not only identifying the dominant contributors but also examining their influence on variations. The evidence-based support will assist in wastewater design optimization, prioritizing sustainable decision-making.

3.1. Impact Assessment of Residential and Industrial Water Treatment Plants

The life cycle impact assessment (LCIA) revealed that the industrial treatment plant incurred a significantly greater environmental burden than the residential one. Higher impacts were observed across all categories in the industrial treatment plant due to the addition of coagulants and increased electricity usage, as shown in Table 5. The pollutant load of whey-based wastewater was almost equivalent to 100 times that of domestic sewage [58]. One cubic meter (1 m^3) of whey-based industrial treated water contributed 7.119 kg CO_2 eq of climate change potential, reflecting the excessive electricity and chemicals required to treat high-strength effluent. On the other hand, 0.135 kg CO_2 eq was required for treating 1 m^3 of residential wastewater. Similar types of trends have been observed for ozone depletion, terrestrial acidification, photochemical oxidant formation, and other categories.

National grid electricity generation, manufacturing chemicals, and transportation activities are the driving forces behind the increased emissions. Comparably higher freshwater eutrophication (kg P eq) and marine eutrophication (kg N eq) indicate that intensified chemical dosage is required to neutralize nutrient-related impacts in industrial treated wastewater. The production and enhanced usage of metal-based coagulants (indirect impact) show a sharp increase in eutrophication, terrestrial, freshwater, and marine ecotoxicity. A rise in fossil depletion from 0.0509 to 2.494 kg oil equivalent and metal depletion from 0.0044 to 0.4199 kg Fe equivalent also reinforces the material- and energy-intensive nature of the industrial water treatment plant. Ranges from 3.46 to 6.11 kg CO_2 eq per cubic meter have been reported in some studies that adopted nutrient recovery in whey-based digestion [59]. Overall, these comparative results highlight the importance of adopting sustainable mitigation strategies for treating high-strength industrial effluents.

Table 5. Environmental impacts per m^3 of wastewater treatment for residential and industrial wastewater treatment plants.

Impact Category	Unit	Residential	Industrial (Whey)
Climate change	kg CO_2 eq	0.135	7.119
Ozone depletion	kg CFC-11 eq	1.70×10^{-8}	1.62×10^{6}
Terrestrial acidification	kg SO_2 eq	0.0007	0.0398
Freshwater eutrophication	kg P eq	1.76×10^{-6}	1.69×10^{-4}
Marine eutrophication	kg N eq	6.61×10^{-6}	5.25×10^{-4}
Human toxicity	kg 1,4-DB eq	0.0080	0.7219
Photochemical oxidant formation	kg NMVOC	0.0002	0.0129
Particulate matter formation	kg PM_{10} eq	0.0002	0.0105
Terrestrial ecotoxicity	kg 1,4-DB eq	2.62×10^{-6}	2.39×10^{-4}
Freshwater ecotoxicity	kg 1,4-DB eq	8.13×10^{-6}	6.64×10^{-4}
Marine ecotoxicity	kg 1,4-DB eq	4.23×10^{-5}	3.84×10^{-3}
Ionizing radiation	kBq U235 eq	2.28×10^{-5}	2.19×10^{-3}
Agricultural land occupation	m^2a	0.0081	0.5160
Urban land occupation	m^2a	0.0013	0.1237
Natural land transformation	m^2	5.1×10^{-6}	3.2×10^{-4}
Water depletion	m^3	0.0018	0.1190
Metal depletion	kg Fe eq	0.0044	0.4199
Fossil depletion	kg oil eq	0.0509	2.4940

3.2. Impact Assessment of Sludge Incineration

Environmental impact assessments of sludge incineration were calculated alongside the earlier conducted life-cycle assessment for direct wastewater treatment, as shown in Table 6. A range of climate change impact (0.135–7.112 kg CO_2 eq per m^3) was observed at the direct wastewater treatment plant, mostly due to electricity consumption and iron (III) chloride. On the contrary, sludge incineration exhibited a range of 0.001 to 0.003 kg CO_2 eq per m^3 for residential and industrial applications, respectively. Similar trends were observed for toxicity-related categories, where sludge incineration showed a substantially lower human toxicity impact than intensive chemical use in direct wastewater treatment. Resource depletion further reinforces that fossil depletion from sludge incineration is limited to 3.45×10^{-3} kg oil eq in industrial settings, which is much lower than the 2.494 kg oil eq for direct wastewater treatment. Although sludge incineration involves additional natural gas use and the use of chemicals for flue gas treatment, their impacts remain marginal relative to the direct wastewater treatment operation. Consequently, sludge incineration does not significantly affect any mitigation strategy from an environmental perspective. Therefore, this study further focused on the design parameters of direct wastewater treatment rather than the sludge incineration.

Table 6. Environmental impacts per m^3 of sludge incineration for residential and industrial wastewater treatment plants.

Impact Category	Unit	Residential	Industrial (Whey)
Climate change	kg CO_2 eq	0.001	0.003
Ozone depletion	kg CFC-11 eq	9.12×10^{-12}	1.12×10^{-11}
Terrestrial acidification	kg SO2 eq	4.09×10^{-6}	4.97×10^{-6}
Freshwater eutrophication	kg P eq	1.98×10^{-8}	3.77×10^{-8}
Marine eutrophication	kg N eq	1.13×10^{-7}	2.70×10^{-7}
Human toxicity	kg 1,4-DB eq	8.96×10^{-5}	6.07×10^{-4}
Photochemical oxidant formation	kg NMVOC	2.53×10^{-6}	4.53×10^{-6}
Particulate matter formation	kg PM10 eq	1.24×10^{-6}	1.93×10^{-6}
Terrestrial ecotoxicity	kg 1,4-DB eq	3.44×10^{-8}	2.27×10^{-7}
Freshwater ecotoxicity	kg 1,4-DB eq	5.08×10^{-7}	3.93×10^{-6}
Marine ecotoxicity	kg 1,4-DB eq	9.39×10^{-7}	6.69×10^{-6}
Ionizing radiation	kBq U235 eq	2.10×10^{-7}	4.37×10^{-7}
Agricultural land occupation	m^2a	3.56×10^{-5}	6.48×10^{-5}
Urban land occupation	m^2a	2.81×10^{-5}	2.20×10^{-5}
Natural land transformation	m^2	2.72×10^{-8}	3.44×10^{-8}
Water depletion	m^3	2.15×10^{-5}	1.29×10^{-5}
Metal depletion	kg Fe eq	4.52×10^{-5}	8.76×10^{-5}
Fossil depletion	kg oil eq	4.13×10^{-4}	3.45×10^{-3}

3.3. Impact Assessment of Design Parameters for Industrial (Whey) Wastewater Treatment

Electricity consumption and iron (III) chloride were identified as the primary contributors to the environmental impacts from the individual design parameter assessment, as shown in Table 7. The contributions of other design components were less significant than those of these two indicators. Electricity was identified as the primary contributor to two significant impact categories: climate change (4.2251 kg CO_2 eq) and fossil depletion (1.7264 kg oil eq). Energy-intensive aeration, pumping, and mixing are the primary drivers achieving those emission levels. The findings align with earlier studies showing that electricity use is the driving force in the activated water treatment system. The generation of electricity from fossil fuel-based sources was identified as the possible cause of these prominent emissions [60,61].

On the other hand, iron (III) chloride 40% in H2O dominates in other categories, such as human toxicity and terrestrial, freshwater, and marine ecotoxicity. The energy-intensive process of iron extraction, chemical synthesis, and solution preparation is reflected in the impact categories of resource depletion, specifically metal depletion (0.3284 kg Fe eq) and water depletion (0.0721 m^3). A moderate range of impact categories was observed for iron sulphate and aluminium sulphate. However, the combined effect of these chemical uses influences the impacts of depletion, toxicity, and acidification. Similar types of trends have been observed in other studies, demonstrating that coagulant production often outweighs electricity consumption in terms of toxicity and resource depletion [62,63].

Transport contributed less across all impact categories but remained significant for climate change, particulate matter formation, and photochemical oxidant formation. Associated fuel combustion with chemical delivery at the plant is a feasible reason behind these emissions. The demand for high electricity and the energy-intensive production of chemical coagulants drive higher environmental impacts in the purification of 1 m^3 of industrial wastewater. Consequently, the specified carbon footprint of individual design parameters provides a snapshot, whereas performing a sensitivity analysis yields meaningful design interventions and an effective energy-reduction strategy.

Table 7. Estimated environmental impacts from design parameters for 1 m^3 of industrial wastewater treatment.

Impact Category	Unit	Iron (III) Chloride, 40% Mix in H_2O	Iron Sulphate	Aluminium Sulphate	Electricity	Transport
Climate change	kg CO_2 eq	2.2120	3.4×10^{-1}	2.4×10^{-1}	4.2251	0.104
Ozone depletion	kg CFC-11 eq	1.6×10^{-6}	2.3×10^{-9}	7.2×10^{-9}	2.2×10^{-8}	1.3×10^{-8}
Terrestrial acidification	kg SO_2 eq	1.2×10^{-2}	1.9×10^{-3}	3.2×10^{-3}	2.2×10^{-2}	5.2×10^{-4}
Freshwater eutrophication	kg P eq	1.3×10^{-4}	2.7×10^{-5}	4.6×10^{-6}	1.8×10^{-6}	1.1×10^{-6}
Marine eutrophication	kg N eq	3.5×10^{-4}	4.3×10^{-5}	3.4×10^{-5}	8.2×10^{-5}	1.7×10^{-5}
Human toxicity	kg 1,4-DB eq	6.2×10^{-1}	3.3×10^{-2}	2.5×10^{-2}	3.9×10^{-2}	5.0×10^{-3}
Photochemical oxidant formation	kg NMVOC	7.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	3.3×10^{-3}	6.1×10^{-4}
Particulate matter formation	kg PM_{10} eq	3.8×10^{-3}	6.0×10^{-4}	9.6×10^{-4}	4.9×10^{-3}	2.0×10^{-4}
Terrestrial ecotoxicity	kg 1,4-DB eq	1.9×10^{-4}	1.5×10^{-5}	1.3×10^{-5}	1.1×10^{-5}	4.9×10^{-6}
Freshwater ecotoxicity	kg 1,4-DB eq	4.1×10^{-4}	6.3×10^{-5}	6.0×10^{-5}	8.6×10^{-5}	4.5×10^{-5}
Marine ecotoxicity	kg 1,4-DB eq	2.9×10^{-3}	4.4×10^{-4}	2.1×10^{-4}	1.9×10^{-4}	8.4×10^{-5}
Ionizing radiation	kBq U_{235} eq	1.7×10^{-3}	3.7×10^{-4}	4.7×10^{-5}	2.2×10^{-5}	1.9×10^{-5}
Agricultural land occupation	m^2a	2.6×10^{-1}	5.2×10^{-2}	8.3×10^{-3}	1.9×10^{-1}	1.2×10^{-3}
Urban land occupation	m^2a	9.5×10^{-2}	1.5×10^{-2}	8.7×10^{-3}	2.7×10^{-3}	1.8×10^{-3}
Natural land transformation	m^2	1.2×10^{-4}	1.7×10^{-5}	2.1×10^{-5}	1.2×10^{-4}	4.4×10^{-5}
Water depletion	m^3	0.0721	0.0014	0.0088	0.0362	0.0006
Metal depletion	kg Fe eq	0.3284	0.0671	0.0130	0.0052	0.0061
Fossil depletion	kg oil eq	0.5763	0.0877	0.0659	1.7264	0.0377

3.4. Ranges in Output and Input Parameters in the Probabilistic Distribution

A robust sensitivity analysis was performed to illustrate the variation in climate change outcomes (kg CO_2 eq) resulting from treating 1 m^3 of wastewater, considering the contributions of individual design parameters, as shown in Figure 2. The conventional residential wastewater treatment plant shows a lower mean of 0.1349 kg CO_2 eq emissions with a standard deviation of 0.0056 and a 90% confidence interval (0.1258–0.1444 kg CO_2 eq). The coefficient value of 4.16% indicated that the design parameters were less sensitive to the outcome in the residential probabilistic distribution. Moreover, it reflected the stable influent and process control, with lower chemical usage and less energy intensity. In contrast, a higher 90% confidence interval range for carbon emissions (6.491–7.822 kg CO_2 eq) was observed in the industrial wastewater treatment, with a mean (7.1195 kg CO_2 eq) and standard deviation (0.4072 kg CO_2 eq), respectively. Associative uncertainties in the chemical supply chain data in AusLCI amplify the variability in higher dosages for the whey digestion scenario. The wider range of the probabilistic distribution is an indicator of the sensitivity of the design parameter, the heterogeneous composition of industrial effluent, and the energy-demanding treatment process.

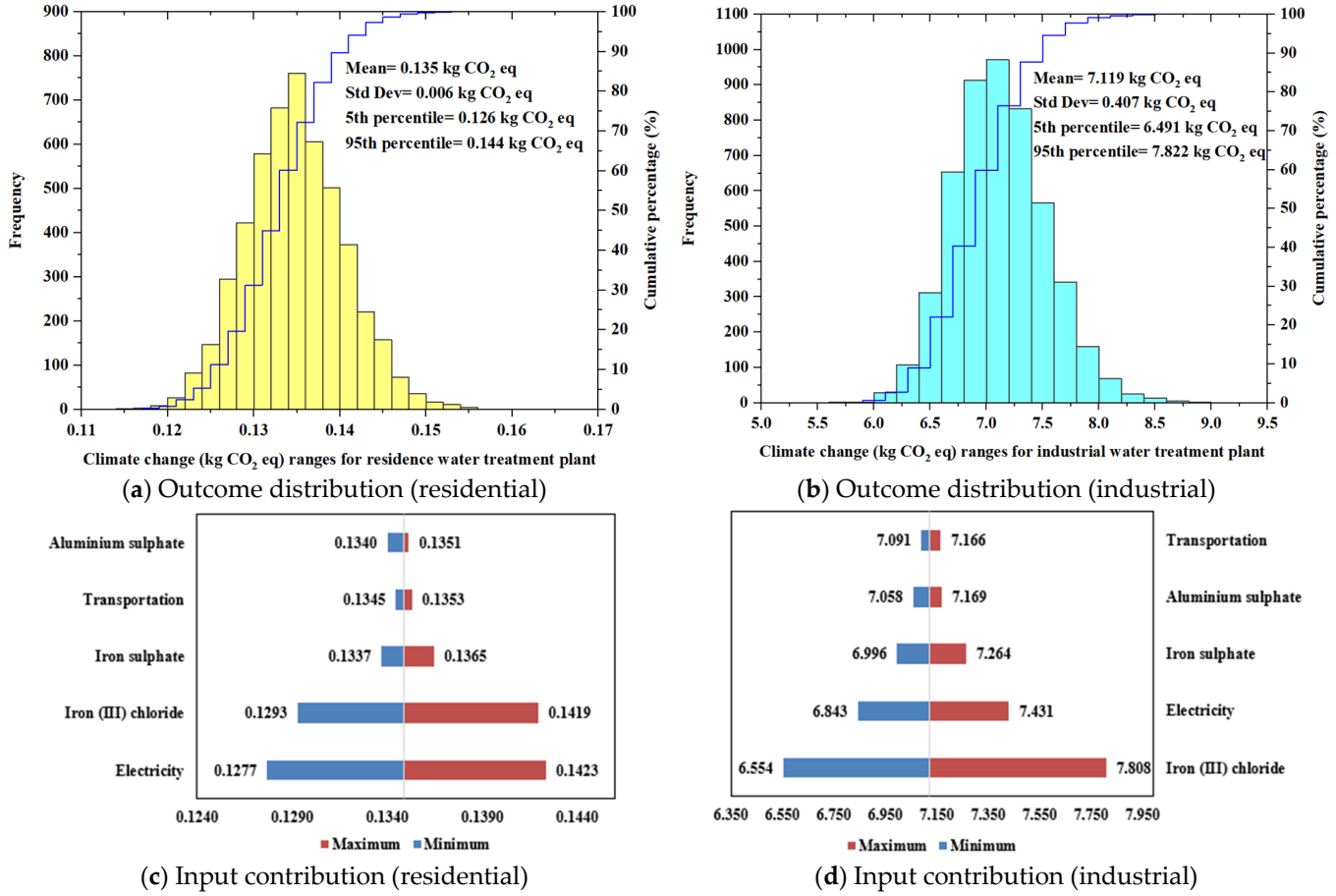

Figure 2. Probabilistic distribution of outcomes and contribution of input variables for the estimated carbon footprint.

Uncertainty analysis of individual parameters was conducted in terms of the magnitude of emissions for the two established systems. Electricity consumption and iron (III) chloride are the dominant sources of carbon footprint, showing ranges of (0.1276–0.1423) and (0.129–0.1419) consecutively. However, their individual contribution to the total emissions was not significant, which could critically destabilize the overall environmental impacts. Conversely, iron (III) chloride and electricity consumption were observed as being the dominant sources of the outcome emissions, exhibiting wider ranges of dispersion around the mean value. Particularly, the change in the level of the CO_2 eq emissions for the chemical coagulants iron (III) chloride (6.554–7.808), iron sulphate (6.996–7.263), and aluminium sulphate (7.058–7.169) reflected their demand and sensitivity for influent pollutant load, while transportation remained a minor contributor. The relevant uncertainty in measuring carbon footprint is closely associated with chemical dosing and electricity consumption in an industrial wastewater treatment plant. Therefore, the correlation of carbon footprint with design parameters will help identify the influence of these components on either increased or decreased application.

3.5. Correlations of Design Parameters with Carbon Footprint

Correlations of individual design parameters revealed variations in CO_2 emissions associated with the treatment of industrial water, as shown in Figure 3. A mean value of 7.1195 kg CO_2 eq with a standard deviation of 0.4072 was observed from this correlation analysis. The variations in operational conditions and input quantities reflect the importance of parameter-specific control rather than random fluctuations.

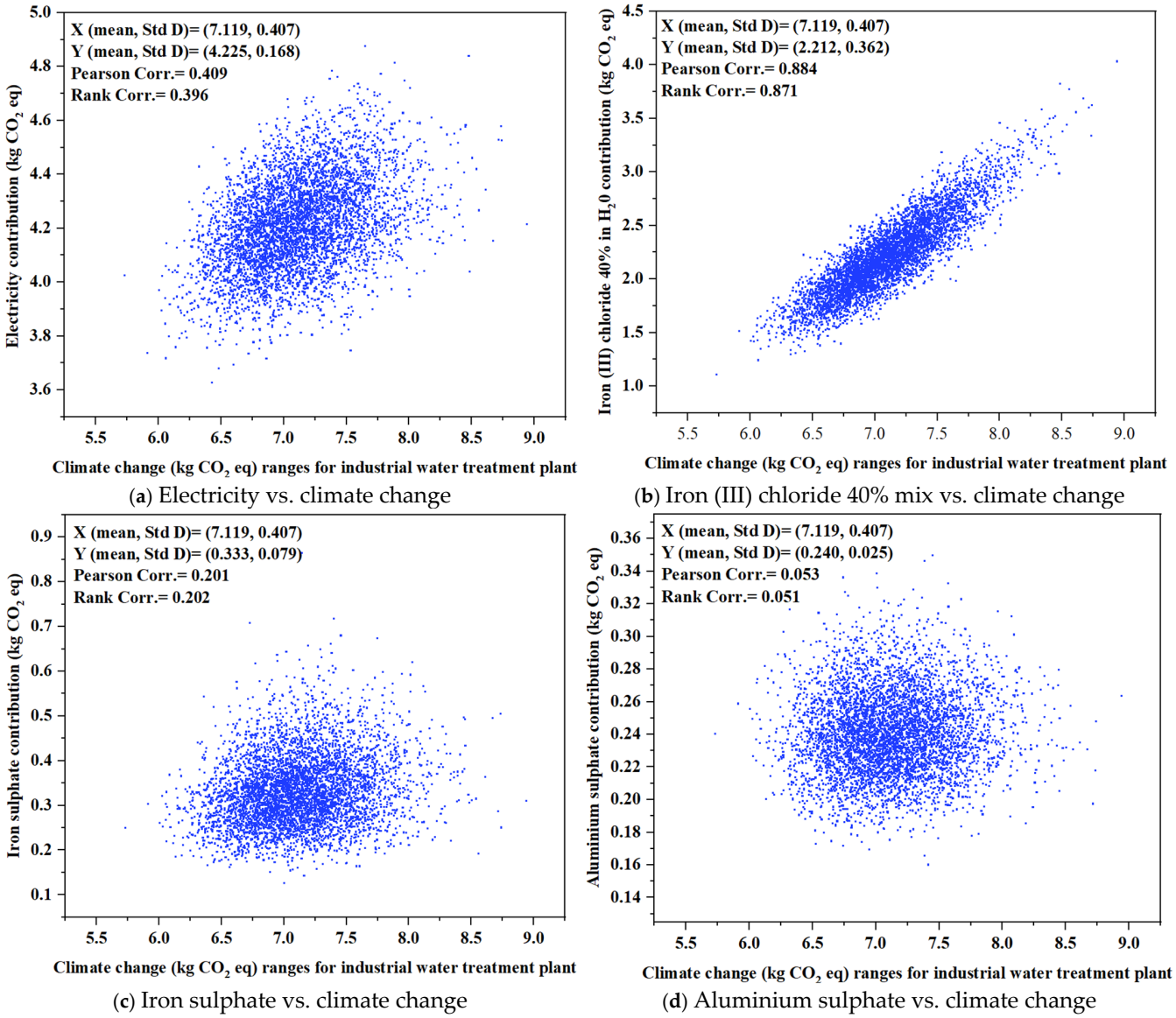

Figure 3. Correlation coefficients of individual design parameters with the total climate change (kg CO_2 eq).

This value indicates moderate dispersion from the determined emission. Electricity consumption and iron (III) chloride represent 59% (4.23 kg CO_2 eq) and 31% (2.21 kg CO_2 eq) of the total emissions, respectively. However, the standard deviation of iron (III) chloride (0.3625) was comparatively higher than that of electricity consumption (0.1681). Iron (III) chloride supply chains exhibited non-linear environmental impacts due to its large adoption in the treatment process. Therefore, Pearson's correlation coefficient and the rank correlation coefficient provided further details and insights into these emission trends. The Pearson correlation (r = 0.8846) indicated that even a small dose of iron (III) chloride can lead to a disproportionate increase in environmental impacts. Therefore, this chemical was identified as a critical leverage point for the emission carbon footprint.

Electricity exhibited a moderate correlation (r = 0.409), indicating that although it made the highest contribution, its variation was lower with increasing usage. On the contrary, the fluctuations in the secondary coagulants showed a weak correlation with emissions for iron sulphate (r = 0.20) and a minor one for aluminium sulphate (r = 0.05). Collectively, the findings of this study emphasize that iron (III) chloride 40% in H_2O is the most influential and sensitive parameter, rather than electricity consumption. Electricity

use contributes to a uniform baseline emission with relatively low variability, whereas the manufacturing of chemical coagulants varies significantly with process control, resulting in large fluctuations. It also provides a scientific basis for prioritizing chemical dosage and a sustainable way of production.

4. Discussion and Recommendations

This study quantified the chemical disinfectants used and their associated environmental impacts in the operational processes of residential and industrial (whey) water treatment plants in Australia. For example, the climate change (kg CO_2 eq) impact potential of industrial treatment exceeded that of residential treatment by several orders of magnitude, with values of 0.135 and 7.119 kg CO_2 eq, respectively.

An uncertainty analysis was performed in addition to the impact assessment to identify the dominant contributors and sensitive parameters of this process. A broader probabilistic distribution in industrial water treatment reflects the non-linear interaction among pollutant load, chemical demand, and electricity consumption. The magnitude and variability of the input parameters highlight the relative findings of this sensitivity-based LCA, as follows:

(a) Electricity consumption is the dominant contributor to the carbon footprint in point-specific impact analysis. It contributes to the highest share of emissions with a mean of 4.225 kg CO_2 eq and a relatively lower standard deviation (0.168). Although its magnitude is dominant, its variation is low compared to other chemical coagulants. It accounts for most of the emissions due to its continuous aeration, pumping, and mixing requirements. A moderate correlation coefficient (r = 0.409) with emissions suggests an increase in emissions with enhanced use, but with limited sensitivity under typical electricity-generation conditions.

(b) Iron (III) chloride represents the most sensitive design parameter with respect to relevant uncertainties, and its variations in application are considerable from a mitigation perspective. It contributes a lower share of emissions (2.112 kg CO_2 eq) than electricity consumption. However, a much higher standard deviation (0.362) reflects the variation of its impact due to the energy-intensive production process. The strong correlation coefficient (r = 0.884) demonstrates that a slight increase or decrease in dosage may disproportionately influence the total carbon footprint.

(c) The findings show a clear contrast between the contributors' dominance and sensitivity in conventional wastewater treatment facilities. Targeted optimization can be a meaningful solution for an emission reduction strategy. Hence, it emphasizes considering upstream supply chain chemical coagulant production and electricity generation sources when designing low-carbon wastewater treatment.

Life cycle analysis prioritizes the important design parameters in this operation to support sustainable design and policymaking. Some of the future recommendations from this analysis have been suggested as follows:

(a) Mercury cell technology for producing iron (III) chloride was identified as the primary leverage point for reducing the overall environmental burden. Adopting membrane-based electrolysis appears to be a feasible solution to reduce emissions from this chemical production process [64]. This will be feasible by improving manufacturing processes, minimizing dosages, adopting alternatives, and evaluating secondary hybrid coagulants.

(b) Coal- and oil-based electricity generation exhibit significant greenhouse gas emissions of 0.927 and 0.839 kg CO_2 eq per kWh, respectively, due to carbon-intensive fuel combustion and energy-intensive fuel refining processes [65]. Natural gas contributes 0.450 kg CO_2 eq per kWh of generation due to its higher conversion efficiency. On the contrary, the representative carbon footprint for per kWh electricity generation

from solar photovoltaic, wind power, and hydropower represents 0.00075, 0.00090, and 0.00488 kg CO_2 eq, respectively. Emissions from renewable sources are associated with solar panel manufacturing, turbine production, and others at the initial stage. Therefore, switching from fossil fuel-based electricity generation to renewable sources will significantly reduce emissions during treatment plants' operational phases and reduce emissions.

(c) Adopting energy-efficient aeration, operation, and pumping technologies in treatment will reduce energy consumption. Secondary coagulants and transportation can be managed by implementing a demand-based process control system.

From the Water-Energy Nexus concept, integrating a probabilistic, uncertainty-based LCA approach into the design of a water treatment plant will ensure sustainability by identifying energy-intensive chemicals and energy demand at the early phase [66].

Limitations of This Study

Despite its novel contribution, this study was intentionally focused on residential and whey-based industrial effluent within the Australian context. Regional-specific assumptions, such as electricity grid composition, transportation distance, and operational processes, have strengthened the consistency of the life cycle inventory (LCI) and its associated uncertainties in this analysis. Therefore, the transferability of absolute emission values needs to be justified by reference to other regions' electricity generation mixes, logistics networks, and regulatory frameworks.

A higher portion of electricity generation from fossil fuels in Australia increases the carbon footprint, and chemical dosing relies heavily on influent wastewater characteristics. Infrastructure construction is excluded from the system boundary to reduce uncertainty associated with long-term assumptions. Although these findings have limitations, the integrated LCA–sensitivity analysis approach is a transferable methodology that can be applied to other suitable regional inventories. This methodological framework provides a transparent basis for evaluating the impact of individual design parameters on reducing emissions from wastewater treatment facilities across different zones.

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