Life cycle assessment of comparing different nutrient recovery systems from municipal wastewater: A path towards self-reliance and sustainability

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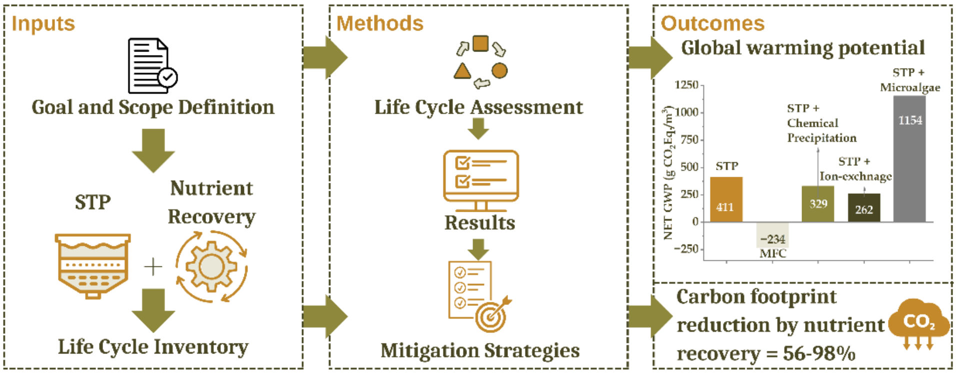
Graphical Abstract



Highlights

LCA of four nutrient recovery methods were compared with conventional WW treatment.

GWP was lowest for the MFC at -234 gCO_2 Eq./m^3 of WW.

Nutrient recovery reduced the C footprint by 56-98%, when compared with urea and DAP.

91% reduction in eutrophication was achieved using nutrient recovery (MFC).

Abstract

Nutrient recovery systems can help to mitigate the negative effects of N and P in WW (wastewater), which when not recovered causes eutrophication in aquatic ecosystems. Using SimaPro (V9.3), the lifecycle assessment (LCA) of four nutrient recovery systems and sewage treatment plant (STP) were compared in this study. The findings showed that a fuel cell with a single-pot WW treatment system can function as a negative emission system with a global warming potential (GWP) of -234 gCO_2 Eq./m^3 of WW. Nutrient recovery reduces carbon footprint by 56–98% when compared to traditional fertilizers like diammonium phosphate (DAP) and urea. One of the main conclusions of this research was that single-pot systems perform better for the environment than add-on systems, which suggests that microalgae could perform better for the environment in a single-pot system. Recovering nutrients from WW not only improves self-reliance in the economy by decrementing the fertilizer import but also saves the environment.

Keywords: Wastewater treatment; Nutrient recovery; Life cycle assessment; Circular economy.

1 Introduction

India's population is expected to increase by 10% between 2030 and 2050 to 1.66 billion (United Nations, 2022). This surge in population increases the demand for freshwater, which in turn increases the wastewater (WW) generation in the country. As of 2021, 72,368 MLD (Million L/d) of sewage is generated in the country, of which only 30% is treated (Downtoearth.org, 2021). Most of the WW treatment facilities are operated at Tier-I and Tier-II cities, while rural regions are ignored. The non-availability of treatment facilities and lack of advanced resource recovery mechanisms has led to the discharge of 52,133 MLD of untreated WW into the water bodies (CPCB, 2021). This untreated discharge of WW not only contaminates the freshwater resources, but also harms the ecology of waterbodies by causing eutrophication due to the presence of nutrients suspended in them. Thus, reducing the level of dissolved oxygen (DO) in water bodies (Sengupta et al., 2015).

WW contains Nitrogen (N) and phosphorus (P) which are usually lost during WW treatment as sludge or discharged after treatment. Recovering and reusing them helps in achieving self-reliance and sustainability. Since N and P are critical components for plant growth, they are used as raw materials in fertilizer production. P is used as an energy source (ADP - adenosine triphosphate), while N is used for building DNA and RNA in plants (Willich and Mathews, 2017). Ammonia (NH_3) is a nitrogen-based fertilizer produced through the Haber-Bosch process from atmospheric N. Meanwhile, P is produced from phosphate rock, which is a non-renewable and limited resource. Moreover, the increasing demand for fertilizer might lead to exhaustion of the global P resources in the upcoming years. Thus, treatment and nutrient recovery from WW not only aids in preventing the contamination of freshwater resources but also abets recovering P thereby achieving sustainable development goal (SDG) 6 before 2030. Nutrient recovery from WW directly relates to the sustainability in four ways; i) reducing the production of synthetic fertilizers which makes the fertilizers industry enroute towards sustainability (SDG 2,12,13, and 15) (Obaideen et al., 2022) ; ii) reduces the nutrient pollution in waterbodies thereby maintaining the sustainable ecology in aquatic systems (SDG 6) (Bhaduri et al., 2016); iii) efficient treatment of WW directly helps in reducing the over usage of freshwater resources (SDG 6); iv) mitigates CO2 emissions caused by WW treatment by production of value-added products (SDG 11) (Obaideen et al., 2022).

Typical urban sewage contains N of 75-125 mg/L, while P ranges between 20-40 mg/L (Metcalf and Eddy, 2017). Earlier nutrient recovery studies show that between 80% and 90% of N and P is recoverable from WW using different treatment methods namely, chemical precipitation, microbial fuel cells, ion-exchange, and microalgae production (Sengupta et al., 2015). Several challenges exist in transitioning these technologies to field-level including robustness, material and energy efficiency, economics, design and optimization, and sustainability analysis.

Nutrient recovery from WW results in liquid fertilizers, struvite, biomass, and sludge as products. Calicioglu et al., (2021) worked on duckweed wastewater treatment with biorefinery options and identified that the pond construction had the highest share for global warming potential (GWP). Meanwhile, it was also reported that the GWP varied between 0.27 – 0.47 kg CO_2 Eq./m^3 of WW treated based on the treatment system employed. In addition, microalgae-based treatment system had a reduction in GWP by about 40%. Similar estimates were reported for struvite crystallization with a GWP of 27 kg CO_2 Eq./kg P (Rodriguez-Garcia et al., 2014). Industrial data suggests that GWP can be negative, while precipitating struvite at -1.4 kg CO_2 Eq./PE/Year (AirPrex, 2022). Microalgae based nutrient recovery options had a wide range of GWP based on the choice of technology between -0.180 and 2.1 kg CO_2 Eq./m^3 of WW (Arashiro et al., 2022; Schneider et al., 2018). This can be attributed to the variation in the energy consumption between different methods employed and end use of algae.

In this work, five scenarios were compared from a LCA perspective for sewage generated from a mid-sized city in India. The scenarios compared include conventional treatment and four-nutrient recovery systems (chemical precipitation, microbial fuel cell, ion-exchange, microalgae cultivation). No previous studies had compared the LCA of nutrient recovery systems that has been mentioned above. In addition, the present study, attempts to conduct attributional LCA for all 5 scenarios and aids in identifying the best performing alternative for conventional treatment method in terms of its environmental performance. Furthermore, this is the first work to report the LCA of nutrient recovery in Indian context. The objective of this work comprises of 1. Estimate the N and P balance of different nutrient recovery systems; 2. Carry out an LCA comparing conventional sewage treatment plant (STP) with four nutrient recovery methods; 3. Analyse and compare the environmental impacts of bio-based and petrochemical fertilizers; 4. Assess the effect of incremental renewable energy usage and their environmental impacts on nutrient recovery systems.

2 Methods

2.1 Goal and scope

The goal and scope of this study is to assess the environmental impacts of sewage treatment plant (STP) and four different nutrient recovery systems. The International Organization for Standardization (ISO) had established a standardized methodology for conducting LCAs that involves four steps: the definition of a goal and scope, inventory analysis, impact assessment, and interpretation of result (ISO, 2006). All four steps have been considered in this study, where *cradle-to-gate* approach was used to carry out LCA. The functional unit used to assess the environmental impacts was 1-m^3 of WW treated/day for 365-days operating period.

2.2 System boundary

The system boundary considered for this study begins with WW entering the treatment plant, wherein different methods are compared. Post to WW treatment and nutrient recovery, the treated water, respective products, and sludge leaves out of the system (Figure 1). Scenario I (Base Case) comprise of the conventional WW treatment with unit operations including primary settling tank, clarifier, sludge thickener, anaerobic digester, decanter, and pump for dewatering and sludge drying. The base case was compared with microbial fuel cell (MFC) (Scenario II), while scenario III, IV and V corresponds to chemical precipitation, ion-exchange, and microalgae based nutrient recovery systems respectively. Scenario III-V used the STP of scenario I followed by nutrient recovery. The information related to mass and energy balance were obtained based on our previous study (Gowd et al., 2022).

2.3 Life cycle inventory

A life cycle inventory (LCI) of energy (e.g., electricity, diesel), chemicals (e.g., coagulation/flocculation, precipitant, adsorbents, and absorbents), direct emissions (e.g., CH_4 and N_2O), nutrients emissions (e.g., discharged to surface water and soil via reclaimed water and biosolids), and avoided products was compiled into the process based on Ecoinvent 3 and Agri-footprint databases. Table 1 represents the operational parameters of the wastewater treatment plant.

2.4 Lifecycle assessment (LCA)

The standard procedure of ISO 14040:2006 was used to assess the environmental impact of the process known as life cycle assessment (LCA). There are two different LCA methods namely attributional LCA and consequential LCA. Among these, attributional LCA was used in this study as the system boundary was limited until the production stage The impact assessment was conducted using SimaPro v9.3.0.3 and Ecoinvent 3 database for background information in mapping the LCI. Impact assessment was carried out using ReCiPe 2016 Midpoint (v1.03) method. A total of 18 impact categories were considered including: global warming potential (GWP), stratospheric ozone depletion, ionizing radiation, ozone formation-human health, ozone formation-terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity, carcinogenic toxicity, non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption.

STP process was developed by adding up the individual unit processes such as primary settling, secondary treatment, secondary clarifier, sludge thickening, anaerobic digestion, sludge dewatering, and return sludge (Sánchez and Martins, 2021). Mechanical equipment such as pumps, thickener, aeration unit, and dewatering unit with energy consumptions were taken from the energy consumption calculations (Table 2). The total energy consumption of STP was 303 kWh/1000 m^3, after deducting the electricity generated from the biogas produced from anaerobic digestion (AD) process.

When it comes to nutrient recovery systems, the entire process of microbial fuel cell happens in a single chamber. Hence, a separate scenario is considered to evaluate its life cycle assessment. Pumping, aeration, and discharging are the major unit operations carried out in microbial fuel cell (MFC) process. On the other hand, chemical precipitation happens in a reactor equipped with agitator to ensure homogeneous mixing of the added chemical in the wastewater. Magnesium oxide or magnesium chloride was used in this process, wherein MgO reacts with N and P to form struvite (Rahman et al., 2014). Producing struvite consumes energy for pumping, mixing, magnesium dosing, discharging, and drying unit operations.

The ion-exchange process recovers the nutrients in the form of crude fertilizer by using adsorbents like zeolites, which can recover about 100 mg of nutrients per gram of zeolite (You et al., 2017). To regenerate the zeolites after recovering crude fertilizer, a brine solution was used. The key ingredients of this process include zeolites and regeneration solution, at the same time, majority of energy was consumed in pumping the zeolite bed and for regeneration activities. Microalgae, the third-generation feedstock, was considered as the future of biorefineries as diverse bioproducts and biofuels can be produced from it. The WW after secondary treatment was used for microalgae cultivation. The growth rate of microalgae used in this study was 1 g/d/L of wastewater treated, which was based on Leite et al., (2019).

In each scenario, all the necessary material and energy consumption, and allocation were considered (Table 3). The electrical energy used in the STP was assumed to be derived from coal power plant in the base case scenario. The effect of reduced global warming potential was studied for an incremental renewable share was considered at 25%, 50%, 75% and 100% respectively.

3 Results and discussion

LCA of four different nutrient recovery systems including chemical precipitation, adsorption, ion-exchange, and microalgae were compared with conventional STP.

Understanding the mass and energy balance provides the LCI for carrying out LCA. In our previous work, (Gowd et al., 2022) detailed mass and energy balance of various nutrient recovery systems were carried out, hence, those data were used for LCI. As this work deals with WW post to secondary treatment, wherein most of carbon (C) was degraded already and only a negligible level exists. Hence, C was not considered for mass balancing. Furthermore, recovery of nutrient such as N and P corresponds to the fertilizer and hence, the balancing them was given crucial importance.

3.1 Mass balance of nutrient recovery systems

Post-secondary treated WW was considered towards nutrient recovery for all scenarios except Scenario-II (MFC). The activated sludge process uptakes 62.3% of N and 37.4% of P, respectively. Sludge cake processing, post to anaerobic digestion has 15.4% N and 19.2% P. Thus, leaving behind 22.3% N and 43.4% P in the effluent (Figure 2a). This N and P after activated sludge process was considered for nutrient recovery using chemical precipitation, ion-exchange, and micro-algae systems. On the other hand, MFC works as a single-pot system to treat raw WW and recover nutrients at the same time (recovery rate = 80%) (Figure 2b). From MFC, N & P were recovered as nutrient-rich solution, which can be used as a raw material for fertilizer production. Scenarios III - V recovers N & P in the form of struvite, fertilizer crude, and microalgae biomass, respectively. Based on the type of nutrient recovery systems, the recovery rate of N & P varied between 11.3 - 17.8% and 35.4 – 36.4%, respectively (Figure 2c). This mass balance information of different nutrient recovery systems was used as LCI.

3.2 Global Warming Potential

Based on the LCI, life cycle assessment was performed using SimaPro. About 18 impact categories were analysed using ReCiPe 2016 Midpoint indicator to study the LCA. Among the impact categories, global warming potential (GWP), freshwater eutrophication, marine eutrophication, and stratospheric ozone depletion are the major environmentally impacting categories in all the scenarios. Conventional STP in *Scenario I* yielded a net GWP of 411 g CO_2 Eq./m^3 (Figure 3a), which was mainly attributed to the energy consumption in aeration tanks, sludge thickening etc. (401 kWh/m^3 WW). Meanwhile, the GWP of STP was also influenced by factors such as type of wastewater, technology used, and materials usage (Dai, 2019). Conventional STPs using activated sludge process reported a similar GWP ranged between 240 – 700 g CO_2 Eq./m^3 (Campos et al., 2016; Chen et al., 2018) (Figure 4a). The increase in GWP was attributed towards modifying conventional processes by extended aeration and denitrification etc. When two treatment systems were combined, GHG emissions increase up to 4 times than the conventional systems (Real et al., 2017).

In contrast, *Scenario-II* (MFC) acts as a single-pot system to treat WW, recovering energy and nutrients simultaneously. Because of this multimodal approach, the energy consumption on the overall treatment and recovery could be reduced substantially, which reduced the overall GWP as well. The GWP of recovered fertilizer in *Scenario II* corresponds to -538 gCO_2 Eq./m^3, while the MFC part consumes a GWP of 304 gCO_2 Eq./m^3, thus, the net GWP of MFC is -234 g CO_2 Eq./m^3 (Figure 3a). Though MFC has a negative GWP, the key issue was towards the scaling up of this technology. MFC lacks proof of concept in scale, wherein till date 10 m^3/d operating capacity was reported to be the highest capacity (Blatter et al., 2021).

Subsequent scenarios (III-V) used WW after secondary treatment for nutrient recovery (Chemical precipitation, ion-exchange, and microalgae). The net GWP of Scenarios III-V were 329, 262, and 1154 g CO_2 Eq./m^3. When compared with conventional WW treatment (Scenario-I), chemical precipitation and ion-exchange offers 20 and 36% reduction in GWP respectively. However, microalgae consumed energy in its race-way pond (550 kWh/m^3) and subsequent unit operations (pumping, aeration, recirculation and harvesting) resulted in higher GWP (85% higher than Scenario-I). Other literature reported similar GWP of 1100 – 2160 gCO_2 Eq./m^3 using microalgae as a nutrient recovery option post to WW treatment (Arashiro et al., 2022; Schneider et al., 2018) (Figure 4b). However, when compared with Schneider et al, this work reports a 53% reduction in GWP.

Campos et al., (2016) reported -180 gCO_2 Eq./m^3, when WW was treated with advanced treatment systems such as SBR and combined with microalgae systems. The above comparison clarifies that microalgae, when combined with other WW treatment might not reduce GWP and hence, the question arises was whether it could be considered for nutrient recovery. The answer to this question lies as when or if microalgae can be standalone WW treatment and nutrient recovery, a single-pot system like MFC. As MFC had a negative emission, only single-pot solutions can solve the environmental issues of nutrient recovery. Moreover, Single-pot systems also reduces the economic burden towards WW treatment.

3.3 Other impact categories

Table 4 corresponds to the values of 5-scenarios towards the 17 other impact categories. Freshwater eutrophication corresponds to the direct impact of excess N and P in WW, when let out leads to algal blooms and growth of aquatic plants. This results in decrease of dissolved oxygen questioning the life in aquatic ecosystems. The N and P balance after secondary WW treatment corresponds to 22.3% and 43.4% respectively, which was let out into waterbodies causing eutrophication. The conventional WW treatment corresponds to a eutrophication levels of 277 g P Eq./m^3, while Rodriguez-Garcia et al., (2014) reported 320 g P Eq./m^3 for similar conditions. The same work reported a reduction of 81% for a struvite precipitation based nutrient recovery from conventional treatment, while in this work 91% reduction was achieved in MFC (10% excess).

Terrestrial ecotoxicity corresponds to the release of effluent and toxic gases in air, land, and waterbodies. Higher energy consumption results in the release of higher concentration of Arsenic and Chromium into the environment due to its presence in coal. These pollutants when enter the food web results in bioaccumulation. Conventional WW treatment (Scenario-I) corresponds to a terrestrial ecotoxicity levels of 386 g 1,4-DCB. When compared with conventional WW treatment, MFC (Scenario-II) reported a 580% reduction (Figure 3b). Other pilot-level studies on nutrient recovery reported a terrestrial ecotoxicity levels of 1000 – 5000 g 1,4-DCB for treating 1 m^3 of WW (Rufí-Salís et al., 2020).

Fossil resource scarcity corresponds to the amount of fossil energy used for various operations during the process. Net fossil oil scarcity was reported in a unit of g oil Eq. The fossil oil scarcity ranged between -36 to 313 g oil Eq. based on the scenario adopted. Bisinella de Faria et al., (2015) reported a fossil oil depletion in the range of 120-130 g oil Eq., when urine from WW was separated and used for nutrient recovery as struvite. Figure 5 represents the characterization of the major impact categories such as a) ozone formation-human health, b) fine particulate matter formation, c) ozone formation-terrestrial ecosystems, d) terrestrial acidification, e) freshwater ecotoxicity, f) marine ecotoxicity, g) human carcinogenic toxicity, and h) human non carcinogenic toxicity for the five scenarios.

Overall, the environmental performance of MFC was reported to outperform other scenarios including microalgae based nutrient recovery systems. The main attribution of MFC was that it was a single-pot system, where in it recovers nutrients as well as treat the WW simultaneously. Whereas, for microalgae systems, treated WW after secondary treatment was used. Hence, further studies on microalgae are necessary to understand its effect on a combined solution as a nutrient recovery and a raw WW treatment system.

3.4 Biofertilizer vs petrochemical fertilizers

One of the objectives of this work was to esimate and compare the impact of bio-based fertilizer produced out of WW treatment with the petro-chemical based fertilizers. In India, three fertilizers were commonly used namely, urea, diammonium phosphate (DAP), mono ammonium phosphate (MAP) (Talboys et al., 2016). The GWP of a fertilizer varies based on a factors such as production process and raw material usage. The GWP of conventional fertilisers varied between 6760 and 8980 g CO_2 Eq./kg of fertilizer (Vellinga et al., 2012). Nutrient recovery to a WW treatment was an add-on process and hence, the GWP of WW treatment was ignored in this comparison. The GWP of fertlizer recovered from various nutrient recovery systems varied between 190 and 3000 g CO_2 Eq./kg. When compared with conventional fertlizers, nutrient recovery options had shown a reduced GWP between 56 and 98% (Figure 6). In addition, recovering nutrients reduces the import burden on the economy (Gowd et al., 2021).

The global nations have pledged to achieve 17 sustainable goals by 2030 to ensure equality, good health, and prosperity of people living across the world. SDG is a qualitative approach that requires quantitative validation for better understanding the effects of any industrial process (Weidema et al., 2020). In this regard the LCA is used to evaluate the environmental performance of given industrial process. This LCA study reveal that the nutrient recovery from WW directly aids in production of biofertilizer which can act as substitute for fossil-based fertilizers thereby enabling to achieve SDG 2, 11, 12, and 15. Meanwhile production of organic fertilizer by recovering nutrients from WW helps to inhibit the water pollution (SDG 6). Detailed mapping of SDGs with nutrient recovery has represented in figure 7.

3.5 Renewable energy as a mitigation strategy

The source of energy or electricity have a greater impact on the overall environmental performance of a WW treatment as well as the nutrient recovery system. The energy source must have a significantly reduced carbon footprint to have a less impact on the environment (Robescu and Presură, 2017). Replacing fossil fuels with renewable energy can have a significant impact towards the reduction of GHGs. In this regard, a stepwise (25%) incremental share of renewable energy was used to analyse the effect of reduction in GWP. Table 5 shows the reduction in GWP based on incremental renewable energy share. It was found that on incrementing the renewable energy share by 25%, 50%, 75%, 100% for all the five scenarios, the GWP reduced by 23%, 47%, 71%, and 94 – 95%, respectively. Usage of renewable energy not only aids in enhancing the environmental performance of the nutrient recovery, but also helps in achieving self-sustainability in agriculture sector. The conventional STP process energized by 75% renewable energy could reduce 71% in GWP. The highest reduction in GWP (96%) was seen for MFC when 100% renewable energy was used to drive it.

3.6 Limitations

Nutrient recovery has the potential to avoid emissions compared with conventional fertilizers. However, the technology has different limitations based on location and adaptation of it. For instance, in developing countries like India, WW collection and treatment has not reached 100%, while advanced nutrient recovery systems are far from reaching reality. Nutrient recovery process has complex stages and substages that must be appropriately evaluated for the technology to be used on an industrial scale. Nutrient recovery systems have reached the demonstration level, which is indicated as TRL 4 – 6. Chemical precipitation and microalgae cultivation have been used at the pilot scale in western countries. Unlike other methods, MFC have not been tested at the pilot scale and need further development.

The life cycle inventory data taken for the nutrient recovery rate is 80% that needs experimental validation for different wastewater. As the WW has high load of bacterial content which might inhibit the nutrient recovery especially in algae growth. In addition, the applications and market value for the recovered products plays a vital role in achieving the feasibility of the system. The energy, water, and land footprint of these systems needs to be analysed to validate its sustainability.

4 Conclusion

The life cycle assessment of four different nutrient recovery systems and traditional wastewater treatment were compared in this study. Form the results, it was identified that about 80% of the P present in the effluent can be recovered by employing single-pot system (Microbial fuel cell). Meanwhile, the maximum reduction in global warming potential of 36% was achieved when nutrient recovery system is combined with conventional wastewater treatment. The nutrients recovered from wastewater have significantly decreased the carbon footprint (56–98%) when compared to conventional fertilizer such as diammonium phosphate and urea. The results of this study demonstrate the necessity of single-pot treatment and recovery systems for improved environmental and economic performance. It is necessary to conduct more research on microalgae as a combined technique for nutrient recovery and wastewater treatment.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare no competing interests.

Abbreviation

ASP	Activated Sludge Process
CPCB	Central Pollution Control Board
DAP	Di-ammonium Phosphate
DO	Dissolved Oxygen
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MAP	Mono Ammonium Phosphate
MFC	Microbial Fuel Cell
MLD	Million Litre per Day
N	Nitrogen
NPK	Nitrogen Phosphorus Potassium
P	Phosphorus
PST	Primary Sedimentation Tank
RSR	Return Sludge Ratio
SBR	Sequential Batch Reactor
SDG	Sustainability Development Goals
SRT	Sludge Retention Time
SS	Suspended Solids
STP	Sewage Treatment Plant
STP	Wastewater Treatment Plant
STR	Stirred Tank Reactor
TN	Total Nitrogen
TP	Total Phosphorus
WW	Wastewater

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Figure 7. Nexus between LCA of nutrient recovery with sustainable development goals.

Table 1.

Parameter	**Value**	**Units**
Average flow to STP	56284	m^3/d
Influent BOD$_5$	400	mg/l
Effluent BOD$_5$	30	mg/l
Influent COD	500	mg/l
Effluent COD	37	mg/l
SS - Influent	12382	kg/d
SS - Effluent	644	kg/d
TN - Influent	5628	kg/d
TN - Effluent	1412	kg/d
TP - Influent	1688	kg/d
TP - Effluent	1023	kg/d
Digestate	2200	m^3/d
Dewatered sludge	278	m^3/d

Table 2.

Step	**Equipment**	**Operation**	**Energy consumption (kWh/1000m^3)**
Primary sedimentation	Pump	Pumping of WW from sedimentation tank to aeration tank	1.50
Aeration	Air compressor	Bubbling of air in aeration tank through diffusers	94.88
Secondary clarifier	Pump	Pumping of WW from aerator to clarifier	1.41
Thickening	Thickener	Sludge (PT+WAS) thickening	139.99
Anaerobic digester	Reactor	Anaerobic digestion of sludge at optimized conditions	15.96
Decanting	Decanter/centrifuge	Removing the excess water content in digested sludge	37.11
Return sludge	Pump	Pumping the return sludge to mix with raw WW after primary treatment	0.13
Energy production	Biogas to electricity	Energy generated from biogas produced in AD process	-3.27

Table 3.

Equipment	**Operation**	**Energy consumption (kWh/1000m^3)**
Scenario II		
Pump	Pumping of WW to the reactor	1.5
Aerator	Continuous bubbling of air	213.2
Pump	Discharge of treated water	1.5
Scenario III		
Pump	Pumping of WW to the reactor	1.55
Agitator	Mixing of WW along with precipitant	6.04
Pump	Discharge of treated water	1.55
Decanter	Solid-Liquid separation to produce struvite	0.03
Scenario IV		
Pump	Pumping of WW to the reactor	1.5
Pump	Regeneration of zeolite bed	3.19
Scenario V		
Pump	Pumping of WW to the raceway pond	1.5
Aerator	Continuous bubbling of air	533
Paddle wheel	Continuous circulation of WW in raceway pond	6.39
Pump	Discharge of treated water	1.5
Decanter	Solid-liquid separation to produce struvite	8.44

Table 4.

Impact category	**Unit**	**Scenario(s)**				
		I (STP)	**II (MFC)**	**III (STP + Chemical Precipitation)**	**IV (STP + Ion-exchange)**	**V (STP + Microalgae)**
Global warming	g CO$_2$ Eq.	411.0108	-234.3471	329.6525	262.1346	1154.7430
Stratospheric ozone depletion	g CFC11 Eq.	0.0001	-0.0084	0.0001	-0.0020	-0.0018
Ionizing radiation	kBq Co-60 Eq.	0.0135	-0.0014	0.0089	0.0092	0.0386
Ozone formation, Human health	g NOx Eq.	0.9535	-0.2769	0.7131	0.6595	2.7303
Fine particulate matter formation	g PM2.5 Eq.	1.0497	-0.0164	0.7015	0.7872	3.0667
Ozone formation, Terrestrial ecosystems	g NO$_x$ Eq.	0.9616	-0.2856	0.7155	0.6632	2.7514
Terrestrial acidification	g SO$_2$ Eq.	1.3664	-1.0854	0.4045	0.6994	3.6666
Freshwater eutrophication	g P Eq.	277.0218	24.0250	317.1889	291.4959	310.2106
Marine eutrophication	g N Eq.	0.0152	-0.0053	0.0123	0.0104	0.0434
Terrestrial ecotoxicity	g 1,4-DCB	386.0967	-1845.7156	-349.0878	-288.1446	550.0928
Freshwater ecotoxicity	g 1,4-DCB	15.0093	-2.7595	10.9252	10.2014	42.7961
Marine ecotoxicity	g 1,4-DCB	19.6530	-5.8756	13.3861	12.6053	55.2839
Human carcinogenic toxicity	g 1,4-DCB	19.4514	3.1770	16.7480	15.6767	57.9194
Human non-carcinogenic toxicity	g 1,4-DCB	241.5167	-300.5069	80.3647	70.8127	595.2356
Land use	m^{2}a crop Eq.	0.0047	-0.0023	-0.0154	0.0026	0.0127
Mineral resource scarcity	g Cu Eq.	0.2161	-4.1853	-4.1712	-1.7030	-1.2353
Fossil resource scarcity	g oil Eq.	109.6395	-36.4769	68.8462	75.3179	313.4239
Water consumption	m^3	3.0643	0.0971	3.0743	3.0966	3.3646

Table 5.

Scenario	**Renewable Energy Share**	**GWP**	**GWP reduction**	**Reduction in GWP from avoided products**	**Net GWP**
Unit	(%)	$gCO_2Eq./m^3$	(%)	$g\ CO_2Eq./m^3$	$g\ CO_2Eq./m^3$
Scenario I	0	411	0	-	411
	25	312.5	23.9		312.5
	50	214.1	47.8		214.1
	75	115.7	71.8		115.7
	100	17.3	95.7		17.3
Scenario II	0	304.2	0	-538	-234
	25	231.5	23.9		-306.5
	50	158.6	47.8		-379.3
	75	85.7	71.8		-452.2
	100	12.8	95.7		-525.1
Scenario III	0	426	0	-96	330
	25	325	23.6		229
	50	224.1	47.3		128.1
	75	123.1	71		27.1
	100	22.1	94.7		-73.8
Scenario IV	0	417.6	0	-155	262
	25	317.6	23.9		162.6
	50	217.6	47.8		62.6
	75	117.6	71.8		-37.3
	100	17.6	95.7		-137.3
Scenario V	0	1310.9	0	-155	1154.7
	25	996.5	23.9		841.5
	50	682.8	47.9		527.8
	75	369	71.8		214
	100	55.3	95.7		-99.6

Figure 1.

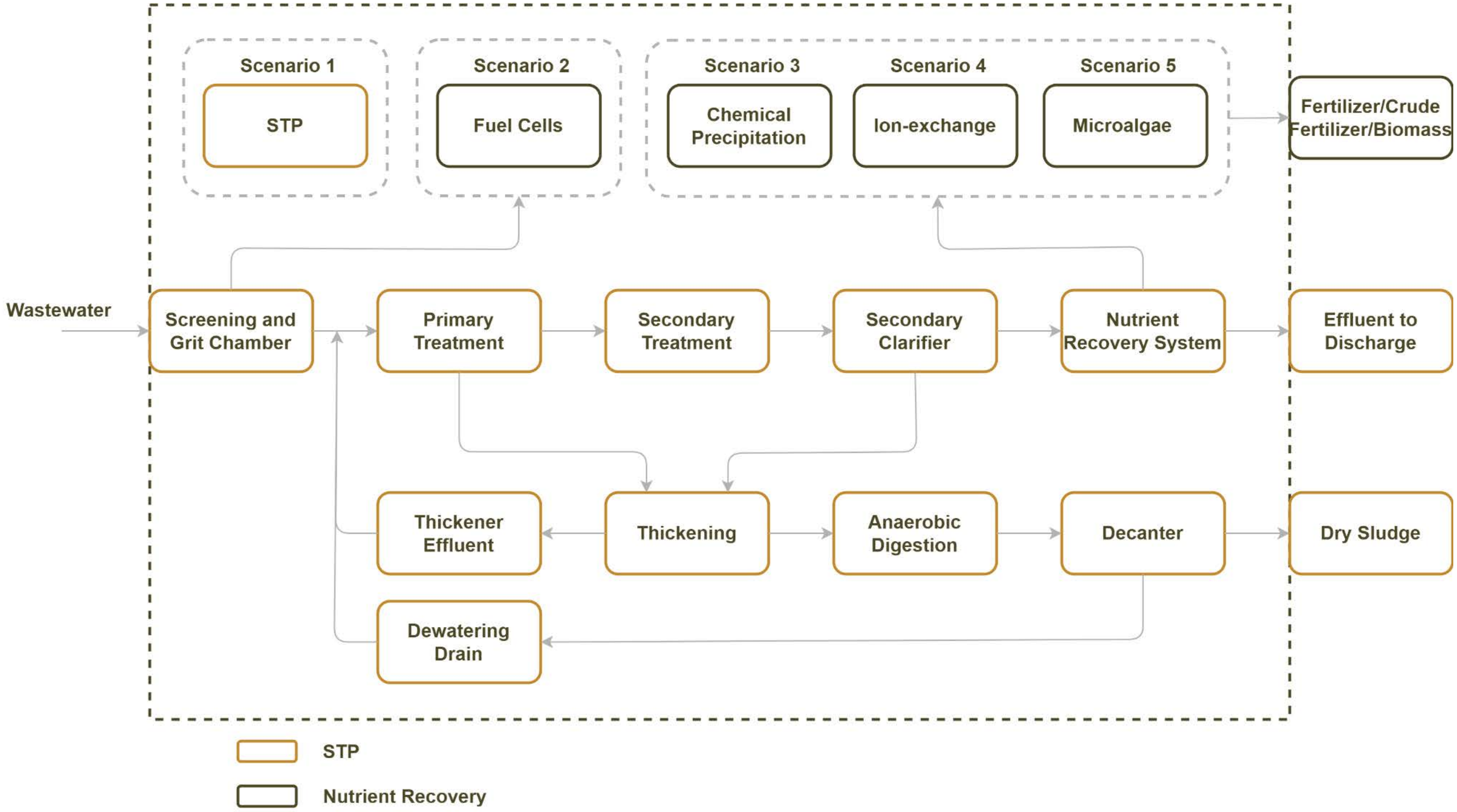

Scenario 1
STP
Scenario 2
Fuel Cells
Scenario 3
Chemical Precipitation
Scenario 4
Ion-exchange
Scenario 5
Microalgae
Fertilizer/Crude Fertilizer/Biomass
Wastewater
Screening and Grit Chamber
Primary Treatment
Secondary Treatment
Secondary Clarifier
Nutrient Recovery System
Effluent to Discharge
Thickener Effluent
Thickening
Anaerobic Digestion
Decanter
Dry Sludge
Dewatering Drain
STP
Nutrient Recovery

Figure 2.

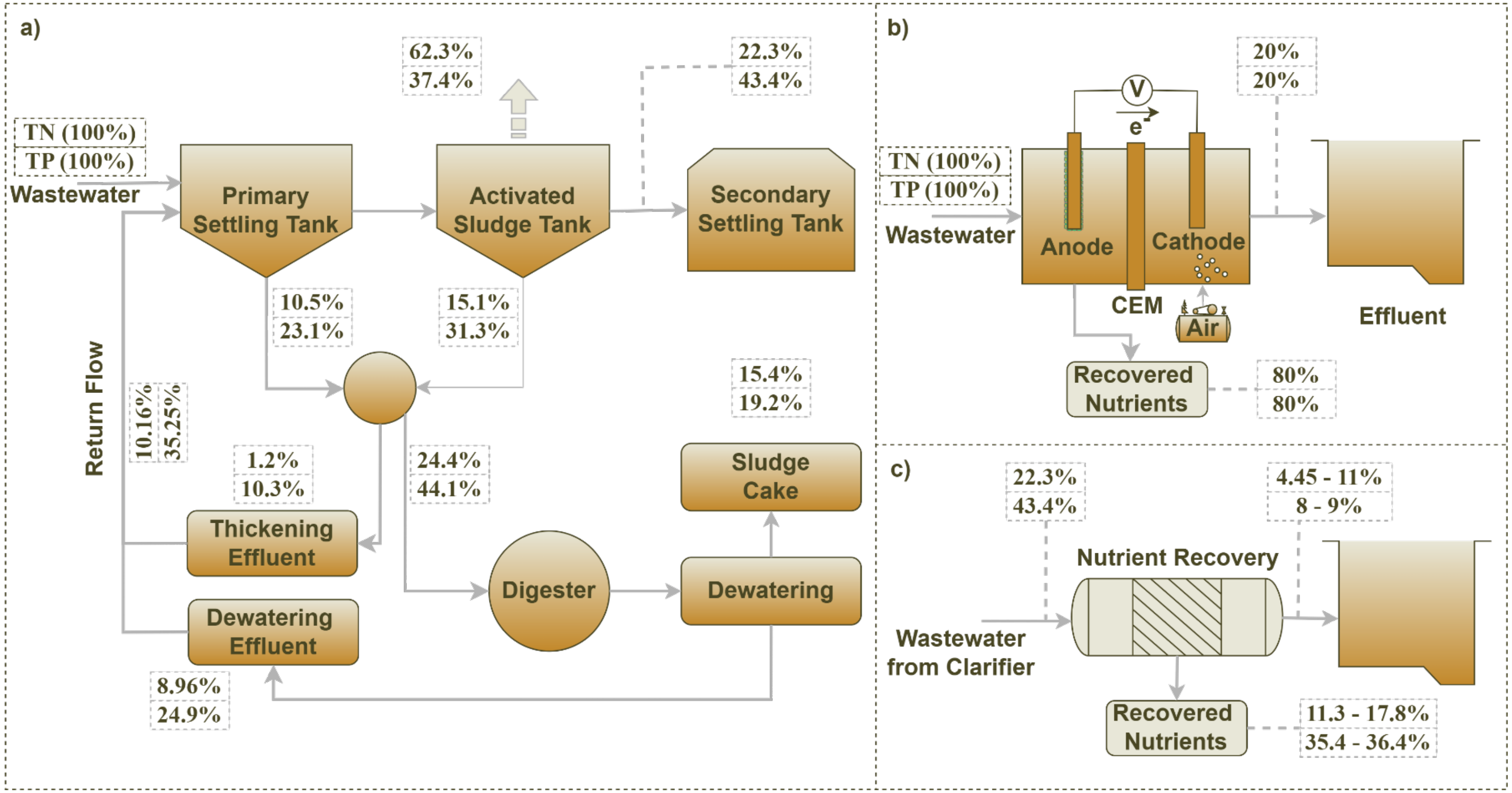

a)
TN (100%)
TP (100%)
Wastewater
Primary Settling Tank
62.3%
37.4%
Activated Sludge Tank
22.3%
43.4%
Secondary Settling Tank
10.5%
23.1%
15.1%
31.3%
Return Flow
10.16%
35.25%
1.2%
10.3%
24.4%
44.1%
15.4%
19.2%
Sludge Cake
Thickening Effluent
Digester
Dewatering
Dewatering Effluent
8.96%
24.9%
b)
TN (100%)
TP (100%)
Wastewater
V
e⁻
20%
20%
Anode
Cathode
CEM
Air
Effluent
Recovered Nutrients
80%
80%
c)
22.3%
43.4%
4.45 - 11%
8 - 9%
Nutrient Recovery
Wastewater from Clarifier
Recovered Nutrients
11.3 - 17.8%
35.4 - 36.4%

Figure 3.

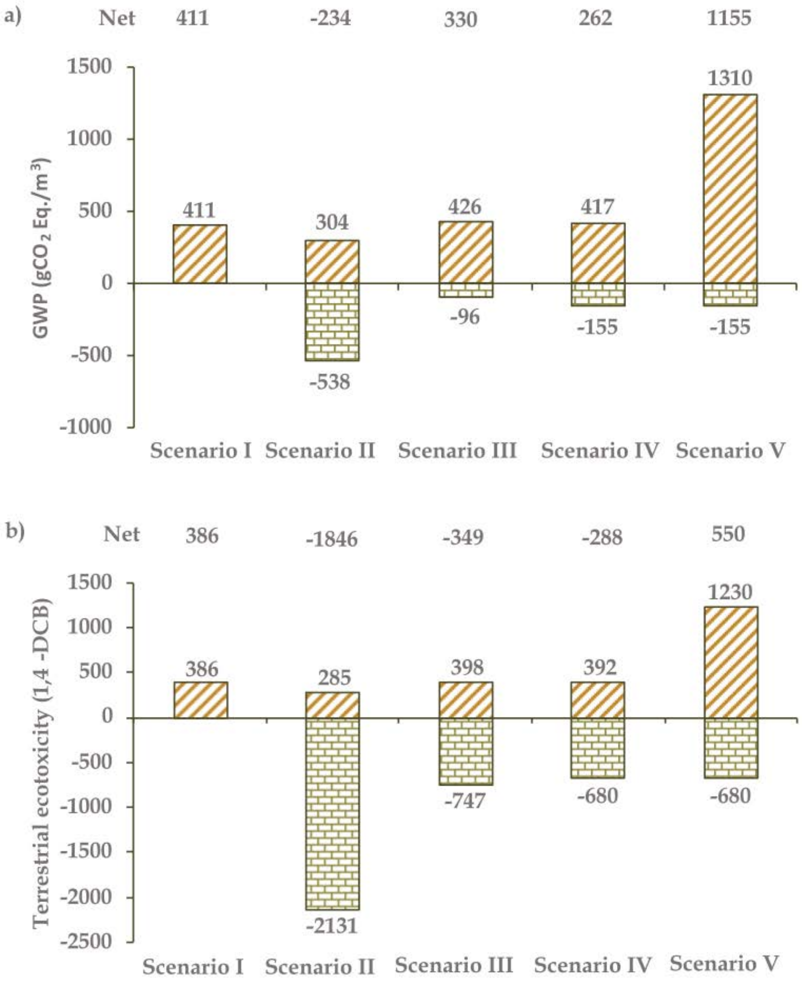

a)
Net
411
-234
330
262
1155
GWP (gCO$_2$ Eq./m^3)
1500
1000
500
0
-500
-1000
411
304
-538
426
-96
417
-155
1310
-155
Scenario I
Scenario II
Scenario III
Scenario IV
Scenario V
b)
Net
386
-1846
-349
-288
550
Terrestrial ecotoxicity (1,4 -DCB)
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
386
285
-2131
398
-747
392
-680
1230
-680
Scenario I
Scenario II
Scenario III
Scenario IV
Scenario V

Figure 4.

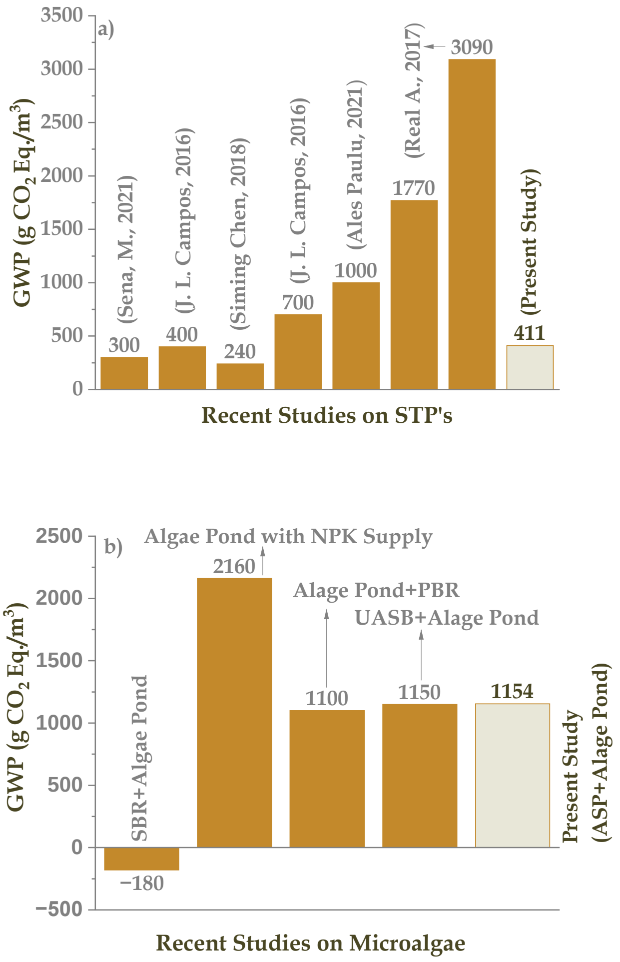
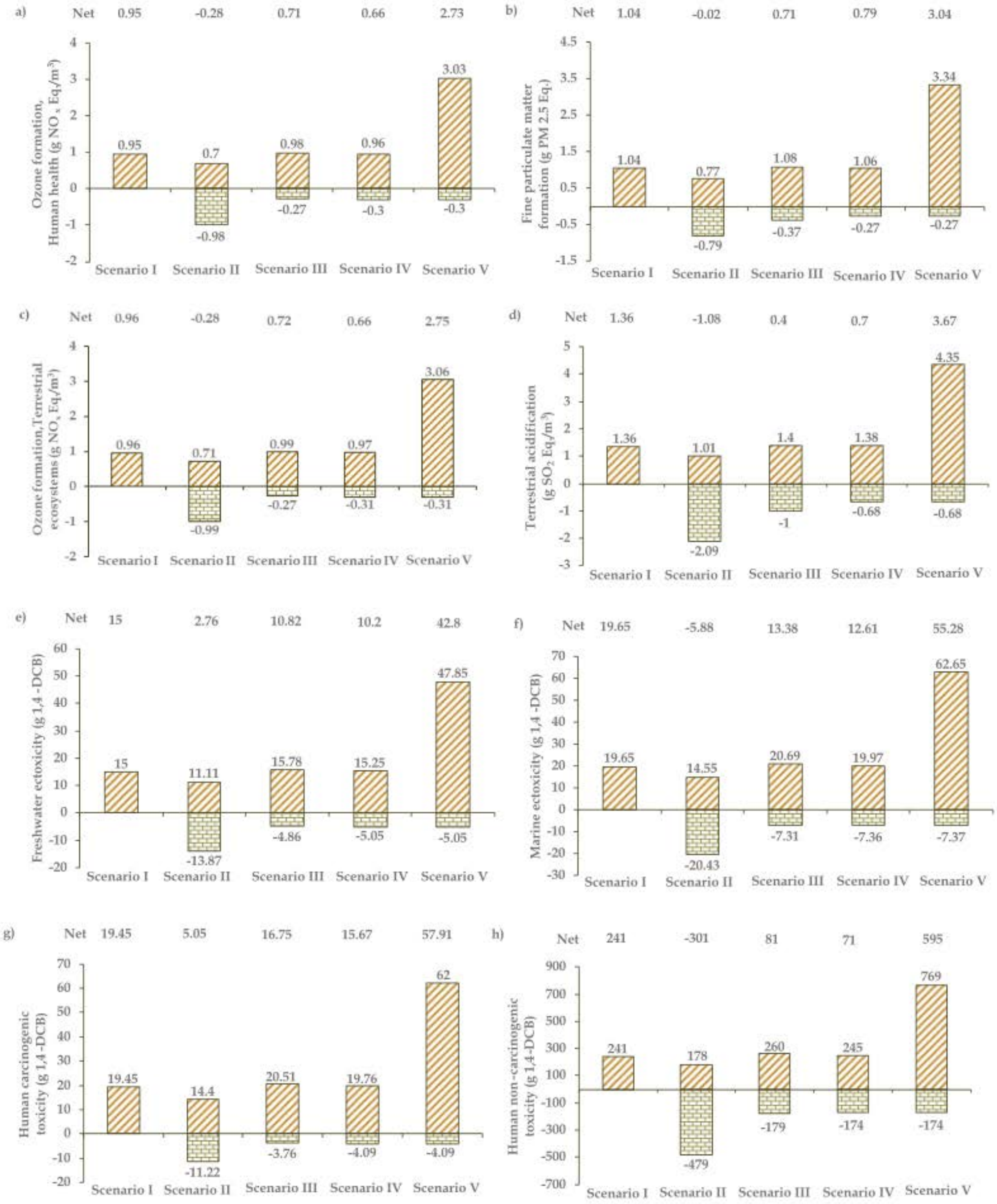
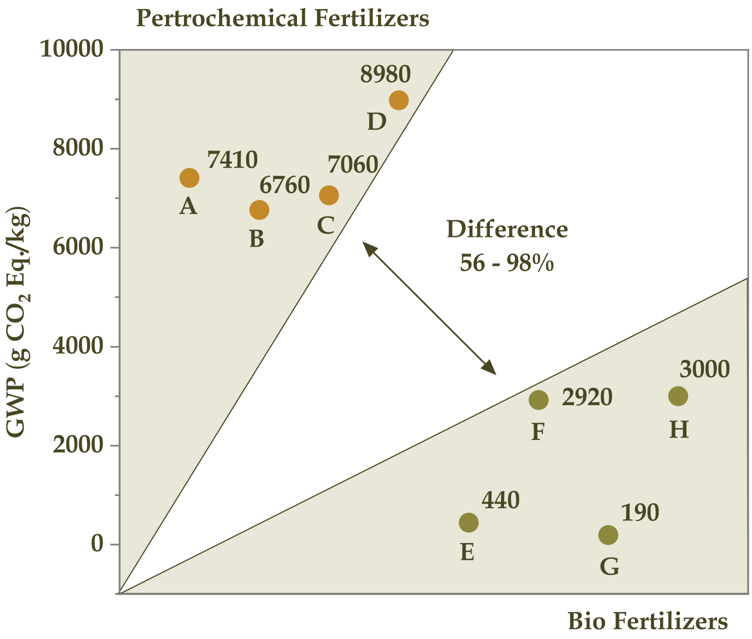

a)
GWP (g CO_2 Eq./m^3)
3500
3000
2500
2000
1500
1000
500
0
(Sena, M., 2021)
300
(J. L. Campos, 2016)
400
(Siming Chen, 2018)
240
(J. L. Campos, 2016)
700
(Ales Paulu, 2021)
1000
(Real A., 2017)
1770
3090
(Present Study)
411
Recent Studies on STP's
b)
GWP (g CO_2 Eq./m^3)
2500
2000
1500
1000
500
0
−500
SBR+Algae Pond
−180
Algae Pond with NPK Supply
2160
Alage Pond+PBR
1100
UASB+Alage Pond
1150
1154
Present Study
(ASP+Alage Pond)
Recent Studies on Microalgae

Figure 5.


a)
Net 0.95 -0.28 0.71 0.66 2.73
Ozone formation, Human health (g NO x Eq/m³)
0.95
0.7
-0.98
0.98
-0.27
0.96
-0.3
3.03
-0.3
Scenario I
Scenario II
Scenario III
Scenario IV
Scenario V
b)
Net 1.04 -0.02 0.71 0.79 3.04
Fine particulate matter formation (g PM 2.5 Eq.)
1.04
0.77
-0.79
1.08
-0.37
1.06
-0.27
3.34
-0.27
c)
Net 0.96 -0.28 0.72 0.66 2.75
Ozone formation,Terrestrial ecosystems (g NOx Eq/m³)
0.96
0.71
-0.99
0.99
-0.27
0.97
-0.31
3.06
-0.31
d)
Net 1.36 -1.08 0.4 0.7 3.67
Terrestrial acidification (g SO2 Eq/m³)
1.36
1.01
-2.09
1.4
-1
1.38
-0.68
4.35
-0.68
e)
Net 15 2.76 10.82 10.2 42.8
Freshwater ectoxicity (g 1,4 -DCB)
15
11.11
-13.87
15.78
-4.86
15.25
-5.05
47.85
-5.05
f)
Net 19.65 -5.88 13.38 12.61 55.28
Marine ectoxicity (g 1,4 -DCB)
19.65
14.55
-20.43
20.69
-7.31
19.97
-7.36
62.65
-7.37
g)
Net 19.45 5.05 16.75 15.67 57.91
Human carcinogenic toxicity (g 1,4 -DCB)
19.45
14.4
-11.22
20.51
-3.76
19.76
-4.09
62
-4.09
h)
Net 241 -301 81 71 595
Human non-carcinogenic toxicity (g 1,4 -DCB)
241
178
-479
260
-179
245
-174
769
-174

553 Figure 6.



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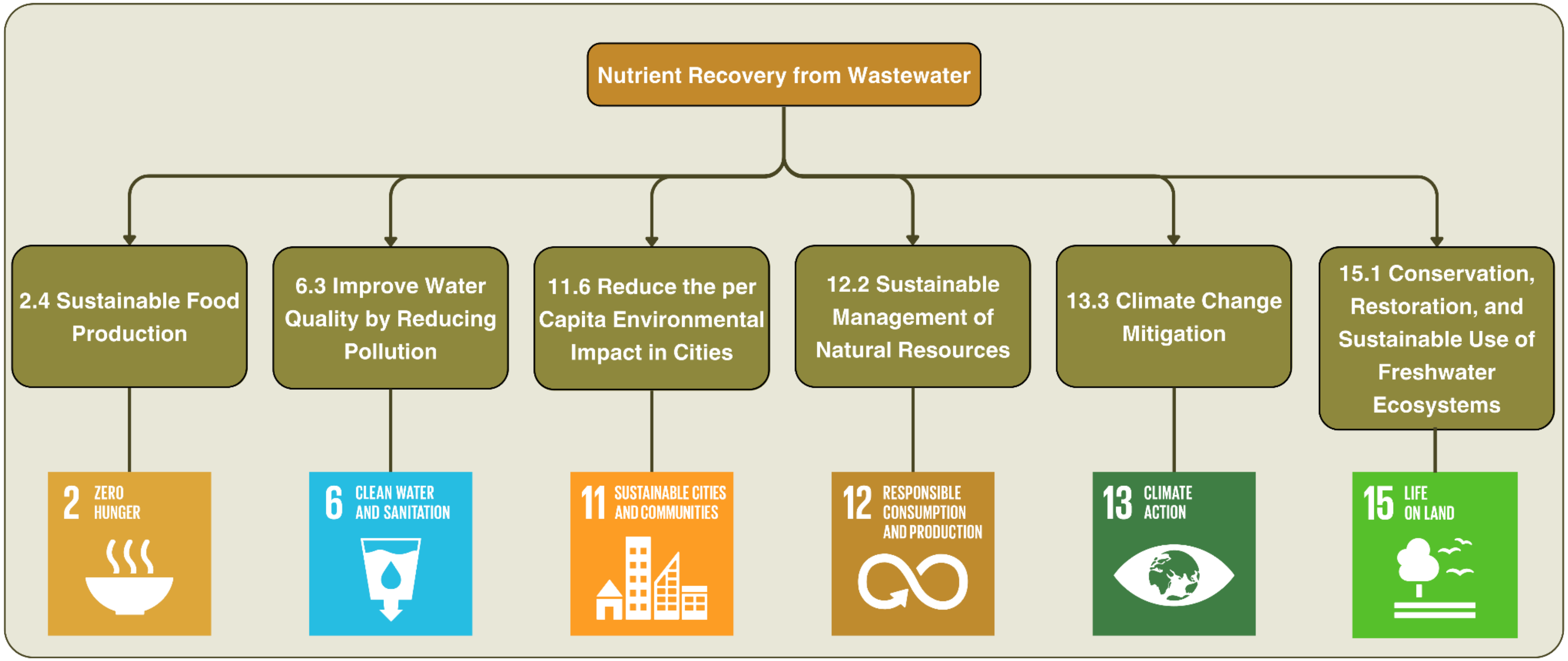
555 Figure 7.



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