Nutrient recovery from wastewater in India: A perspective from mass and energy balance for a sustainable circular economy

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Abstract

Limited global phosphorus availability and increased eutrophication due to discharge of nitrogen pushed everyone to rethink the way, on how to recover nutrients. Wastewater is a potential source to recover N and P, while in India, it is scarcely explored. Understanding nutrient recovery systems involve exploring individual unit operations, sizing, and their energy consumption. Most studies on nutrient recovery from wastewater have focussed on retrieving, while least studies focused on mass and energy balance, which holds the key for its application potential. In this work, four different nutrient recovery system was compared, when added to an STP plant for a mid-size city in India. The results indicate that fuel cells consume the lowest energy at 216.2 kWh/1000m^3, while microalgae used the highest energy at 943.3 kWh/1000m^3. However, from a cost point of view except microalgae (78.6$/1000 m^3) other nutrient systems did not yield any savings.

Keywords: Nutrient recovery; wastewater in India; mass balance; energy balance; economic analysis

1. Introduction

Fertilizer consumption across the world stood at 191 Mt as of 2019 of which P corresponds to 46 Mt (Statista.com, 2022). As of 2022, India consumes about 7.5 Mt of P (The Fertilizer Association of India, 2022), and the overall fertilizer import is estimated at Seven Billion USD (Gowd et al., 2021). P is one of the rare-earth elements, which is projected to last for the next 80 years (Cordell and White, 2011). P is widely used in industries as fertilizers, flame retardants, batteries, steel production, catalysis, and feed phosphates. Hence, recovering them as much as possible holds the key for a sustainable circular economy. Most of the P and N run-off from various streams after its use and end up in aquatic ecosystems causing eutrophication leading to algal blooming. Besides, it is anticipated that global warming and climate change might accelerate the effect of algal bloom causing a serious environmental threat (Environmental Protection Agency, 2020). Recent data shows that around 50% of N-based fertilizer is discharged to the water bodies due to run-off (Our World in Data, 2021).

Wastewater (WW) is a potential source of run-off, where the excess fertilizers were discharged on to aquatic ecosystems causing algal blooming. Hence, recovering the nutrients from WW plays a pivotal role in avoiding the environmental threat of eutrophication and extinction of P. Important nutrient recovery systems reported in the literature includes chemical precipitation, filtration, ion-exchange, microbial fuel cells (MFC) and microalgae cultivation (Diaz-Elsayed et al., 2019). Several laboratory works have reported the nutrient recovery rate varied between 65% and 90% (Sengupta et al., 2015) for distinct systems. Most of the literature is available at a laboratory-scale, while pilot scale information or industrial operation is limited. Few industries have implemented pilot systems on nutrient recovery across the world, including Ostara (Ostara, 2019), Colsen Water & Environment (Colsen water, 2020) and Algalwheel (Algaewheel, 2019). Industrial implementation of these nutrient recovery systems needs understanding from a multi-dimensional perspective, including mass and energy balance, economics, and sustainability of the processes.

Mass and energy balance (M&E) provides a deeper understanding on the overall system through dissection and flows, which is a fundamental and critical principle. Moreover, M&E balance helps to identify the bottleneck of a process at-scale, which is uncommon in laboratory works and literature. Few studies have reported the M&E balance of sewage-treatment plants (STP) where post-secondary treatment, N and P availability was reported to be between 17-25% and 35-65%, respectively (Ekama et al., 2011; Mininni et al., 2015). Likewise, other N removal methods such as denitrification, ammonia oxidation, anammox process can reduce it up to 1% (Garrido, 2013). However, M&E balance of STP incorporating with nutrient recovery systems was not reported in the literature before. This is the first work to calculate the M&E balance of various nutrient recovery systems from WW.

In this work, four different nutrient recovery systems were compared in cohesion with STP for a mid-sized city in India. The nutrient recovery systems used for the assessment include a) chemical precipitation; b) ion-exchange; c) microbial fuel cells; d) microalgae cultivation. The objective of this work include: 1. Design the conventional STP with nutrient recovery systems; 2. Estimate the mass flow across each unit operation; 3. Assess the energy balance and consumption of STP and nutrient recovery systems; 4. Correlate the economic savings of distinct nutrient recovery systems.

2. Methods and calculations

2.1 Location and basic statistics

Vijayawada, a mid-sized Indian city (2.14 million population in 2020) was chosen to study the mass and energy balance of integrating nutrient recovery to an existing wastewater (WW) treatment system. By 2035, population of the city was projected to be 2.9 million (Macrotrends, 2020). All the calculations in this work were based on the projections for 2035. The average per capita WW generation in India was 110-120 l/p/d (Ministry of Jal Shakti, 2020). There were six treatment plants in operation, which decentralizes the WW treatment. Each plant was assumed to have equal capacity for the WW treatment and integrating it with nutrient recovery.

2.2 Design of conventional sewage treatment

Commonly, WW in the city was treated using an activated sludge process (ASP), which includes primary, and secondary treatment. The treatment plant was designed as per the typical inflow and outflow obtained from literature (Table 1). The primary treatment involves screening and sedimentation, while secondary treatment includes aeration and clarifiers. Each plant had a flowrate of 56,284 m^3/day, while the screens and storage tanks were designed to hold a peak capacity of 3X of the typical flow. The WW collected from the city was stored in the storage tanks, which was sent to treatment process (Figure 1).

The treatment process starts with screening, where it removes large particles present in the wastewater. Normally, screening and grit-chamber was a gravity-based process and hence no energy was consumed. After screening, the wastewater enters the primary sedimentation where solid particles with higher specific gravity ($\rho \geq 2.5$) settles down. These sedimentation tanks have a detention time of two hours. The flowrate and volume of the sedimentation tanks were calculated based on Eq. (1) and (2), where Q_{max} - maximum flow rate (m^3/d); t - detention time (hours); d - diameter of the tank (m); and D - depth of the tank (m).

$$Volume\ of\ sewage\ (m^3) = \frac{Q_{max}\ (\frac{m^3}{d})}{t\ (h)\ \times 24\ (h)} \qquad (1)$$

$$Volume\ of\ the\ tank\ (m^3) = \pi \times \frac{d^2}{4}\ (m^2) \times D\ (m) \qquad (2)$$

Subsequently, the treated water enters the aeration tank for the removal of biologics. Based on the inflow, up to 10 aeration tanks were considered to treat the WW. Such tanks have a detention time varied between 3 and 72 h based on the strength of WW. F/M ratio (ratio of influent BOD (kg) to the amount of microorganisms (kg)) and MLSS (mixed liquor suspended solids) determines the volume of the aeration tank which was given in Eq. (3), and (4), where Q_{max} - maximum flow rate (m^3/d); V- volume of the tank (m^3); Y_0 - initial BOD concentration (mg/L); X_T - MLSS concentration (mg/L). Typical F/M ratio and MLSS ranges between 0.15 – 0.3 and 1500 – 2500 mg/L, respectively (Arceivala, 2000). The lower bound values of F/M (0.15) and upper bound value of MLSS (2500 mg/L) were considered in calculation due to the low concentration of suspended solids in WW. Eq. (5) and (6) governs the calculation of hydraulic retention time (HRT) and volumetric loading rate (VLR). Return sludge ratio (RSR) and sludge retention time (SRT) of the aeration tank were calculated by using Eq. (7) and (8), where SVI corresponds to sludge volume index (mg/L); Y_0 - influent BOD (mg/L); Y_E - effluent BOD (mg/L); θ_c- SRT (days); α_y (1.0) and K_e ($0.66d^{-1}$) were constant values. Typical SVI values range between 50 and 150mg/L; 140 mg/L was used for calculation purposes. Aerating the tanks and pumping the WW needs energy through unit operations such as compressors and pumps. Next to aeration, the treated water enters the secondary clarifier, where in excess sludge settles down and clear water was discharged to further processes (nutrient recovery). The volume of secondary clarifier was calculated by totalling the inflow and recirculated flow over a day (Eq. (9). Box 1 shows the design calculations for the conventional STP (Supplementary file S1).

$$Average\ flow\ in\ each\ tank\ \left(\frac{m^3}{d}\right) = \frac{Q_{max}\left(\frac{m^3}{d}\right)}{No.of\ aeration\ tanks(n)} \qquad (3)$$

$$\left\{\frac{Influent\ BOD\ (kg)}{Microorganisms\ (kg)} = \frac{Flowrate\ (m^3/d)}{Volume\ (m^3)} = \frac{Influent\ BOD\ (\frac{mg}{L})}{MLSS\ concentration\ (\frac{mg}{L})}\right\}$$

$$= \left\{\frac{F}{M} = \frac{Q_{max}}{V} = \frac{Y_0}{X_T}\right\} \qquad (4)$$

$$Hydraulic\ retention\ time\ (t) = \frac{Volume\ of\ tank\ (m^3)}{Flowrate\ (m^3/d)} = \frac{V}{Q} \qquad (5)$$

$$Volumetric\ loading\ rate = Flowrate\left(\frac{m^3}{d}\right) \times \frac{Influent\ BOD\ \left(\frac{mg}{L}\right)}{Volume\ of\ the\ tank\ (m^3)}$$

$$= Q \times \frac{Y_0}{V} \qquad (6)$$

$$Return\ Sludge\ Ratio\ (RSR) = \frac{Q_R}{R} = \frac{Total\ Flow\ Rate\ (\frac{m^3}{d})}{Return\ Sludge\ Flow\ Rate\ (\frac{m^3}{d})}$$

$$= \frac{X_T(\frac{mg}{L})}{\frac{10^6}{SVI(\frac{mg}{L})} - X_T(\frac{mg}{L})} \qquad (7)$$

$$VX_T\left(m^3 \times \frac{mg}{L}\right) = \frac{\left\{\alpha_y . Q\left(\frac{m^3}{d}\right)\left(Y_0\left(\frac{mg}{L}\right) - Y_E\left(\frac{mg}{L}\right)\right)\theta_c\right\}}{1 + K_e\,\theta_c} \qquad (8)$$

$$Volume\ of\ the\ Secondary\ Clarifier\ (m^3) = \frac{Total\ Inflow\ (m^3/d)}{24\ (h)}$$

$$= \frac{Inflow\ \left(\frac{m^3}{d}\right) + Recirculated\ Flow\ (\frac{m^3}{d})}{24\ (h)} \qquad (9)$$

2.3 Design of nutrient recovery systems

The conventional WW treatment was followed by incorporating the nutrient recovery systems. In this work, four majorly used nutrient recovery systems were studied for their efficiencies. This includes: 1. Chemical precipitation; 2. Ion-exchange; 3. Fuel cells; 4. Microalgae cultivation. Of these four methods, except microalgae cultivation other methods offer direct fertilizer equivalent replacements, while the latter ends up a crude for industries, including food, pigment, cosmetics, and energy.

2.3.1 Chemical precipitation

Nutrient recovery by chemical precipitation works on the principle of recovering N, and P as struvite by precipitating the treated WW with Mg compounds. The precipitation happens in a stirred tank reactor (STR), where the number of batches and average flow per batch was calculated based on Eq. 10 and 11, respectively. The mass of Mg needed for precipitation were calculated were based on Eq. (12), which uses a molecular species balance of 1:1 for Mg:P (Rahman et al., 2014). Agitator used in the process consumes energy of 250 kW. The precipitation process takes 30 min to complete, which was then sent to a decanter for moisture removal. Decanter consumes energy of 1 kWh/m^3, which was followed by air drying (Szepessy, 2018). The assumption used for the calculations of all nutrient recovery methods such as initial N concentration, P concentration, and recovery rate was given in Table 2. Box 2 shows the calculation for the sizing and volume of each nutrient recovery system (Supplementary file S1).

$$No. of\ bathces\ (n) = \frac{Q_{max}\left(\frac{m^3}{d}\right)}{Volume\ assumed\ for\ each\ reactor\ (m^3)} \quad (10)$$

$$Average\ flow\ per\ batch\ (m^3/batch) = \frac{Q_{max}\left(\frac{m^3}{d}\right)}{No. of\ batches\ (n)} \quad (11)$$

$$Mg^{2+} + NH^{4+} + PO_4^{3-} + 6H_2O \ \rightarrow \ NH_4MgPO_4.6H_2O \quad (12)$$

2.3.2 Ion-exchange

Ion-exchanges uses zeolites to capture the nutrients from WW, post to secondary treatment. Several zeolites' efficiencies range from 80-90% (for N and P) (Gowd et al., 2021). Ze-Ca based zeolite was considered in this study due to its efficiency and abundancy in the Indian context. These zeolites were placed in a single-column reactor as packed beds, where the nutrients uptake, at a rate of 100 mg/g of zeolite (Wan et al., 2017). Ion-exchange based recovery systems employs a batch process, where in it takes 30 min for adsorption, followed by 30 min of regeneration. Based on the overall cycle and operation, eight batches were used in a day for the total volume of 59,262 m^3/d (post-secondary treatment). Regeneration of zeolites uses 10% concentration of Brian solution (NaCl) (Eq. 13 and 14). The flowrate and volume for the packed bed column was calculated like chemical precipitation (Eq. 10 and 2). Pumping the WW and regeneration of zeolites needs energy at the rate of 45kW.

$$Ze - PO_4^{3-} + NaCl \ \rightarrow Na^{+}Ze + PCl_3 \quad (13)$$

$$Ze - NH_4^{+} + NaCl \ \rightarrow Na^{+}Ze + NH_4Cl \quad (14)$$

2.3.3 Fuel cells

Fuel cells use the microbial fuel cell (MFC) to recover nutrients from WW and / or to produce energy. The key issue in MFC was lack of proof of concept on scalability of sizes greater than 10 m^3/d (Blatter et al., 2021). Commonly, the product of MFC systems was a fertilizer-crude. Based on the largest scale available as on the date (1000L), the reactor sizing and volume were calculated by extrapolating it (Blatter et al., 2021). Assuming carbon cloth electrodes were used in a rectangular reactor, the volume of the reactor was calculated based on Eq. 15. Adding aerator improve the nutrient recovery efficiency greater than 80%, which consumes air at the rate of 0.43 m^3/s. For aeration, air compressor was used with an energy rating of 250kW (Alibaba.com, 2022a). Feeding the WW and discharging them after MFC needs one pump with an energy rating of 45 kW.

$$Volume\ of\ the\ reactor\ (m^3) = Flowrate\ (m^3/d) \times HRT\ (h) \qquad (15)$$

2.3.4 Microalgae cultivation

Unlike other nutrient recovery processes, microalgae-based systems recover N and P as biomass. Raceway pond with a depth of 0.3-m was assumed, which was operated with a paddle wheel at a velocity of 0.25 m/s (Marsullo et al., 2015) . Different pumps were used at the rate of 45 kW and 1.5 kW for pumping of WW and recirculation, respectively. Aeration improves the efficiency of raceway pond, which consumes air at the rate of 0.8 m^3/s. The growth rate of microalgae of 1 g/L was used for calculating the mass balance (Alabi et al., 2009) with a detention time of 10 days (Sharma et al., 2020). Energy rating of various equipment such as pumps, aerator, and decanter are 45kW, 125kW, and 8kW**,** respectively (Alibaba.com, 2022b, 2022a; Murthy, 2011).

2.4 Mass balance

Mass balance was calculated based on the fundamental inflow of 56,284m^3 WW/d. Eq. 16 shows the generic mass balance, in which generation and consumption are zero, as mass can neither be created or nor be destroyed in a system. The amount of mass entering into and out of each unit operations were designed based on Dionisi, (2021) and Mininni et al., (2015). Key parameters considered in the mass balance include mass of water, suspended solids (SS), volatile suspended solids (VSS), total nitrogen (TN), and total phosphorus (TP). The system was assumed to be in a steady-state condition for calculation purposes. Besides the overall balance, individual species balance, including SS, N and P was also studied. Based on mass balance from STP, nutrient recovery balance was calculated based on the various process methods. Each species was balanced to have greater accuracy of the system. The nutrient recovery processes were assumed to be operated in batch mode and stead-state conditions.

$$Accumulation = Input + Generation - Output - Consumption \qquad (16)$$

2.5 Energy balance

Energy balance provides key understanding on the intricacies of how each unit operation and type of process behaves towards attaining a specific product. Firstly, the energy consumption in each unit operation of a STP was calculated based on power rating. Except anaerobic digestion, rest of the unit operation in STP consumed energy. Next, the energy consumption of each nutrient recovery processes was calculated and added to the energy consumed from STP. Finally, the energy consumption of STP and nutrient recovery were presented in a functional unit of kWh/1000m^3.

In a STP, energy was consumed in pumping (45kW), thickening the sludge (1.5kW), dewatering (1.5kW), aeration (250 kW), and agitation (75kW) (Arceivala, 2000; Checalc, 2022; Füreder et al., 2018; Huber Technology, 2021; Ross and Bell, 2013;

Szepessy, 2018). Pumping the clarified water to the nutrient recovery and discharging them used a pump of 45 KW each. Chemical precipitation used a stirrer with a power rating of 85kW and decanter of 1 kW. On the other hand, ion-exchange used energy for regeneration of zeolites (45kW), which was used for 30 min/batch (Alibaba.com, 2022b; Checalc, 2022; Szepessy, 2018). In contrast, fuel cells use an aerator of 250 KW. This was because no STP was needed in fuel cells, and it was a single-pot treatment and recovery systems. Microalgae consumed energy for aeration (125 kW), recirculation of WW (1.5kW), and decanter (8kW) (Alibaba.com, 2022a; Murthy, 2011).

Eq (17) shows the power calculation of the pump used in various processes, where Q - flow rate (m^3/s); ρ - density of WW (kg/m^3); H - head of water to be pumped (m); g- gravity of earth (m/s^2); η- efficiency of pump (%). The head of WW was assumed to 10, with a pump efficiency as 75%.

$$Power\ P\ (kW) = \frac{Q\left(\frac{m^3}{s}\right) \times \rho\left(\frac{kg}{m^3}\right) \times g\left(\frac{m}{s^2}\right) \times H(m)}{\eta\ (\%)} \qquad (17)$$

3. Results

Mass and energy balance on the WW generated from a mid-sized city in India (Vijayawada) was carried out on a conventional STP followed by the addition of nutrient recovery systems. The WW generated from the city was divided into six equal plants and data for one plant was calculated. It was extrapolated to calculate the overall M&E balance for the WW generated from the city. Furthermore, based on the cost and volume of the product from nutrient recovery and energy consumed, comprehensive cost saving was estimated.

3.1 Mass and energy balance of Sewage Treatment Plant

3.1.1 Mass balance

Conventional STP employing an activated sludge process (ASP) was used to assess the mass balance. The WW passes through the screens, grit chamber, primary sedimentation tank (PST), aeration tank and finally to the secondary clarifier. Sludge generated from sedimentation and aeration tank was sent to thickening it. Anaerobic digester (AD) receives the sludge, which was converted to biogas (energy), while the treated water was discharged as per Indian standards. Key parameters that were considered in the mass balance include: 1. Water balance; 2. Suspended solids (SS); 3. Volatile suspended solids (VSS); 4. N; 5. P.

As mentioned above, the total WW generated from the city was divided equally among six plants. Each plant had a WW flow rate of 56284m^3/d, while negligible mass was lost through screens and grit chamber, as they account for larger chunks. Along with recycling stream, fresh WW enters the primary settling tank, where in 97% of it flows to the aeration tank, while the remaining ends up as a sludge (Figure 1). Biological treatment happens in the activated sludge tank, where in most of the C and N was converted to sludge. Sludge corresponds to 6%, which enters the thickener, while the remaining 94% of mass moves to the secondary settling tank. Negligible mass was lost during the secondary settling tank as most of the SS were removed in earlier processes.

The thickener thickens the sludge from PST and ASP, where in the liquid fraction is stored as thickening concentrate (3332 m^3/d), while the sludge was digested in AD (2200 m^3/d). Post to the AD process, a dewatering system recycles the water fraction to the thickening concentrate (1922 m^3/d). Both the thickening concentrate and dewatered fraction were recycled to the primary settling tank (5254 m^3/d). Treated water loses 93% of the suspended solids, which enters to a nutrient recovery system for the recovery of N (1412 kg/d) and P (1023 kg/d).

Like overall mass flow, Figure 1 shows the movement of SS, VSS, N, and P, respectively. The raw WW contains 5628 kg N/d, and 1688 kg P/d, while post to the STP process, 25% and 60% of it remains, respectively (Figure 2). About 58% of the inflow N was lost as ammonia gas during the treatment, while a smaller fraction ends in dewatered sludge, drain, etc. (Figure 2a). When it comes to P, 26% were lost during dewatering, followed by 12.6% as phosphine along with ammonia (Figure 2b). The majority of N and P was lost during the WW treatment, which will affect the nutrient recovery. However, MFC acts as a single-pot wastewater treatment system which recovers nutrients as well. Hence, it was expected that the N and P loss will be lower.

3.1.2 Energy balance

The overall energy usage of a conventional STP stood at 303.05 kWh/1000 m^3, where three-unit operation consumes the most energy. This includes thickener (46.2%), aeration (31.3%), and decanter (12.2%). Table 3 shows the split of energy consumption of various unit operations in an STP. Over various processes, three pumps were used that corresponds to the total energy consumption of 1.05%. These pumps were used in a primary settling tank, secondary clarifier, and return sludge process. Box 3 shows the detailed energy balance calculations of an STP plant (Supplementary file S1). Anaerobic digestion was the only process which could produce energy while other processes consumed it (-3.27%). However, it was minimal as sludge contains fewer organic compounds, which did not yield high biogas yield like food waste or lignocelluloses.

3.2 Mass and energy balance of nutrient recovery systems

3.2.1 Mass balance

Post to STP, the treated water enters the nutrient recovery systems at a flow rate of 56,112 m^3/d. However, microbial fuel cells act as a single-pot WW treatment system which had a flow rate of 56,284 m^3/d. For chemical precipitation, Mg was added based on available P on a ratio of 1:1 (Table 2). MgO of 209 kg was added to precipitate the struvite fertilizer. The reaction runs for 30 min, after which dewatering and open drying results in the final product (Struvite). The product struvite corresponds to 1930 kg/d, which is after the removal of 981 kg/d of moisture. However, 20% of P after secondary treatment of STP could not be recovered, which end up in discharge. Figure 3 shows the overall mass balance of various nutrient recovery systems post to secondary treatment of an STP. Of the four methods compared, MFC, and microalgae were sustainable options for a circular economy, which were bio-based solutions. The product of crude algae corresponds to 16.8 t. However, Microalgae needs an overall volume 561,100 m^3, that was calculated based on the retention time of 10 days (Box 2). In total, 18 raceway ponds were needed to process the WW of 56,112 m^3/d.

Ion-exchange processes use zeolite bed and Brian's solution to cover crude fertilizer. Zeolites of 305 kg was used while Brian solution of 10% was used to regenerate the zeolite beds. About 1948 kg was obtained as a crude fertilizer, while the remaining liquids were discharged. Unlike other methods, MFC was a stand-alone WW treatment system, where in microbes consumes the SS as well as generate crude fertilizer. About 5.5 t of crude fertilizer could be obtained in MFC process, which was the highest among all methods compared, as no N or P was lost during the STP process. This shows that MFCs could be a potential solution to WW treatment and nutrient recovery. Nonetheless, the scalability at large, reproducibility and membrane fouling or damage issues needs to be looked upon.

3.2.2 Energy balance

Energy consumptions of the different nutrient recovery systems were reported based on kWh/1000 m^3. Table 4 shows the energy consumption of various unit operations of the nutrient recovery systems. The calculations for each method were highlighted in Box 4 (Supplementary file S1). Except MFC, other methods used STP along with nutrient recovery. The total energy consumed for the nutrient recovery along with STP was 312.1, 307.8, 216.2 and 943.3 kwh/1000m^3 for chemical precipitation, ion-exchange, MFC, and microalgae, respectively (Figure 4). On a stand-alone nutrient recovery, ion-exchange needed the lowest energy consumption (4.7 kwh/1000m^3). Aeration corresponds to 56% of the total energy consumed in the microalgae based nutrient recovery.

3.3 Cost savings

Based on the mass and energy balance calculated above, overall cost savings of various nutrient recovery systems were estimated. Chemical precipitation and ion-exchange used chemicals such as MgO and Brian's solution that cost 0.37 and 0.1 \$/1000 m^3, respectively (Table 5). Chemical precipitation and microalgae based nutrient recovery systems end up as a dry product, while the other two methods were in a liquid state. Hence, the market price of crude fertilizer was lower (140 \$/t) than the dry product (struvite – 300 \$/t, algae – 490 \$/t). The cost of energy consumption was highest for microalgae at 67.92 $/1000m^3, while it was lowest for the MFC at 15.57 $/1000m^3. The net saving was calculated based on the difference between overall product sold and cost of chemicals and energy consumed. The net savings were negative for all nutrient recovery systems, except for microalgae, which had savings of 78.6 $/1000m^3. However, the land and capital expense of microalgae was not considered in this calculation, depicts the reality of viable systems. MFC had overall savings of -1 $/1000m^3, which could be a profitable method as when technology gets matured.

4. Discussion

The energy consumption of a variety of WW treatments varied between 10 and 225kWh/1000m^3, depending on the process (Government of Rajasthan, 2011; Ministry of Housing and Urban Affairs, 2016; Water and Sanitation Program, 2008). Figure 5 shows the energy comparison of different conventional WW treatment systems along with the energy consumption of this work with nutrient recovery combined. Ranieri et al., (2021) reported an energy consumption of 1.02 kWh/m^3 for aerobic digestion, while anaerobic digestion consumed 0.43 kWh/m^3. This work used an activated sludge process, which consumed energy at 0.30 kWh/m^3, which shows that the results of distinct methods were in the comparable range. Except microalgae, other nutrient recovery methods were in comparable range with literature. Microalgae consumed higher energy due to aeration and dewatering units. This is one of the critical challenges, when microalgae are used as a nutrient recovery process.

Besides energy consumption, microalgae use 18 raceway ponds that needs an area of 462 acres (da Cruz and do Nascimento, 2012). This corresponds to one of the six plants in operation, and for treating the WW from the entire Vijayawada city will need 2772 acres. The city size equals to five-fold of the area that is needed for the microalgae cultivation. This raises the question of land mass availability, and this might not be a feasible option for an urban setting. However, when adequate land is available such microalgae systems can be considered.

The maximum size of a MFC reported in literature was 1000 L (Blatter et al., 2021). This system had a COD removal efficiency varied between 80 and 95%, while this study considered a BOD removal efficiency of 92%. The volume of the reactor needed for the MFC to treat the WW generated from Vijayawada would be in the range of 6 (Number of plants) X 8 (reactors per plant) X 15000 m^3 (maximum size of reactor assumed). Operating such a high-volume reactor needs reproduceable and reliable results at pilot scale. Besides, MFC has several technical issues such as fouling, membrane regeneration, electrode performance and higher costs (Breheny et al., 2019). These hindrances need to be addressed for MFC to be applied at-large scale.

5. Conclusion

Recovering N and P from WW helps in attaining a sustainable circular economy. However, its effect on mass and energy balance is least understood. In this work, four different nutrient recovery systems were compared including chemical precipitation, ion-exchange, fuel cells and microalgae from M&E perspective. The key findings include: 1. Fuel cells consumed the lowest energy at 216.2-kWh/1000m^3; however, their scalability needs to be addressed; 2. Microalgae consumed the highest energy due to aeration and decanter processes at the rate of

943.3-kWh/1000m^3; 3. No nutrient recovery system except microalgae (78.6$/1000m^3) could yield savings on the recovered mass.

CRediT author statement

Sarath C. Gowd: Methodology, Data Curation, Formal Analysis, Investigation, Visualization, Writing - Original Draft

Karthik Rajendran: Conceptualization, Writing - Review & Editing, Supervision, Project Administration

Declaration of competing interest

The authors declare no competing interests.

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Abbreviation

ASP	Activated Sludge Process
BOD	Biological Oxygen Demand
CPCB	Central Pollution Control Board
EPA	Environmental Protection Agency
FBR	Fluidized Bed Reactor
HRT	Hydraulic Retention Time
MFC	Microbial Fuel Cell
MLSS	Mixed Liquor Suspended Solids
N	Nitrogen
P	Phosphorus
PST	Primary Sedimentation Tank
RSR	Return Sludge Ratio
SBR	Sequential Batch Reactor
SRT	Sludge Retention Time
SS	Suspended Solids
STP	Sewage Treatment Plant
STR	Stirred Tank Reactor
TF	Trickling Filter
TN	Total Nitrogen

TP	Total Phosphorus
VLR	Volumetric Loading Rate
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WW	Wastewater

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Table 1. Design considerations of wastewater used to calculate the mass and energy balance of a sewage treatment plant (Metcalf and Eddy, 2017; National Green Tribunal, 2019)

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Table 4. Estimated energy consumption of four nutrient recovery systems compared and extrapolated for the Vijayawada city.

Table 5. Summary of mass, energy, and economic assessment comparing the four nutrient recovery systems (Alibaba.com, 2022c, 2022d; Davis et al., 2016; Global Petrol Prices .Com, 2021)**.**

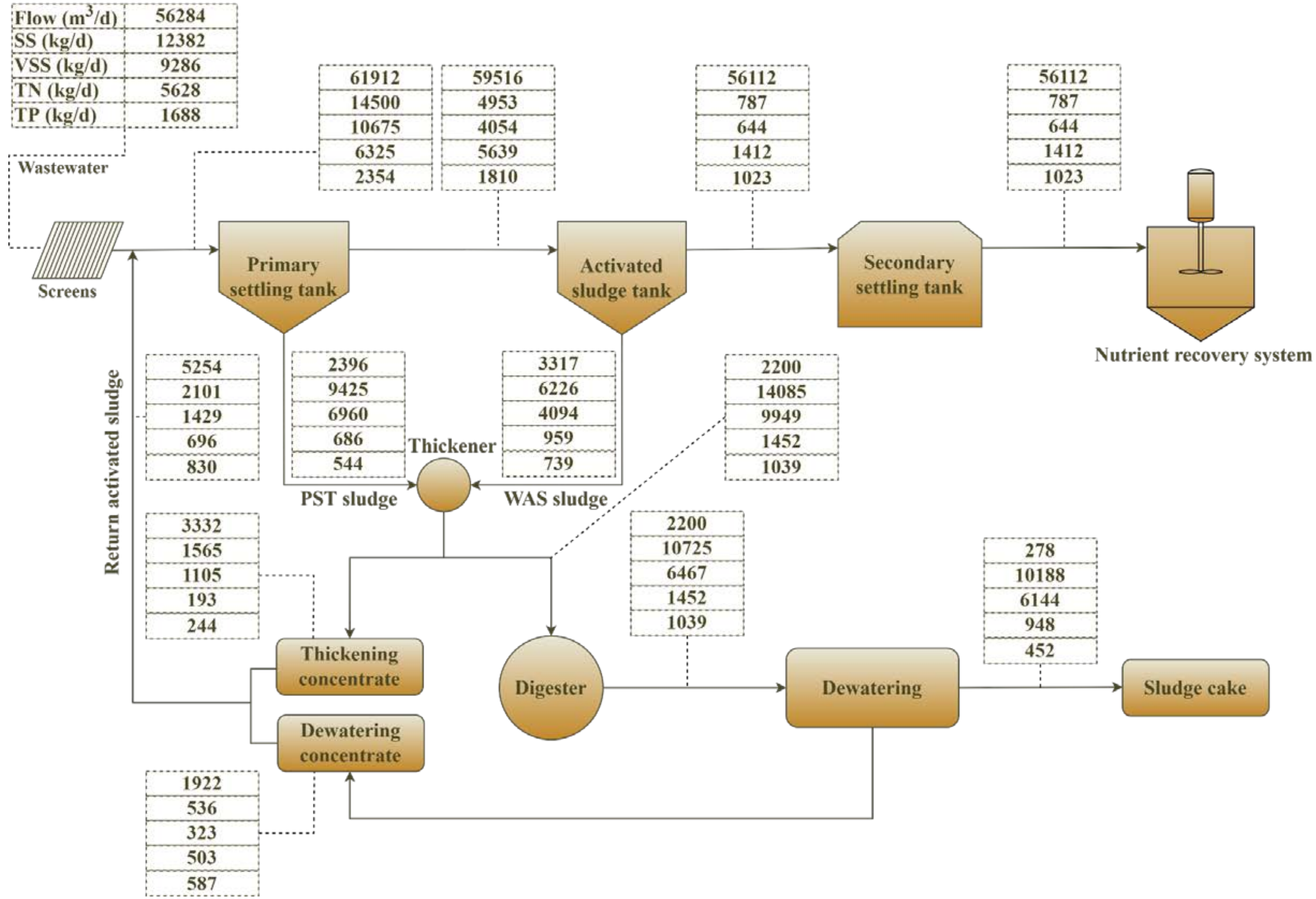

Flow (m3/d) 56284
SS (kg/d) 12382
VSS (kg/d) 9286
TN (kg/d) 5628
TP (kg/d) 1688
Wastewater
Screens
61912 14500 10675 6325 2354
59516 4953 4054 5639 1810
56112 787 644 1412 1023
56112 787 644 1412 1023
Primary settling tank
Activated sludge tank
Secondary settling tank
Nutrient recovery system
Return activated sludge
5254 2101 1429 696 830
2396 9425 6960 686 544
3317 6226 4094 959 739
2200 14085 9949 1452 1039
Thickener
PST sludge
WAS sludge
3332 1565 1105 193 244
2200 10725 6467 1452 1039
278 10188 6144 948 452
Thickening concentrate
Digester
Dewatering
Sludge cake
Dewatering concentrate
1922 536 323 503 587

Figure 1.

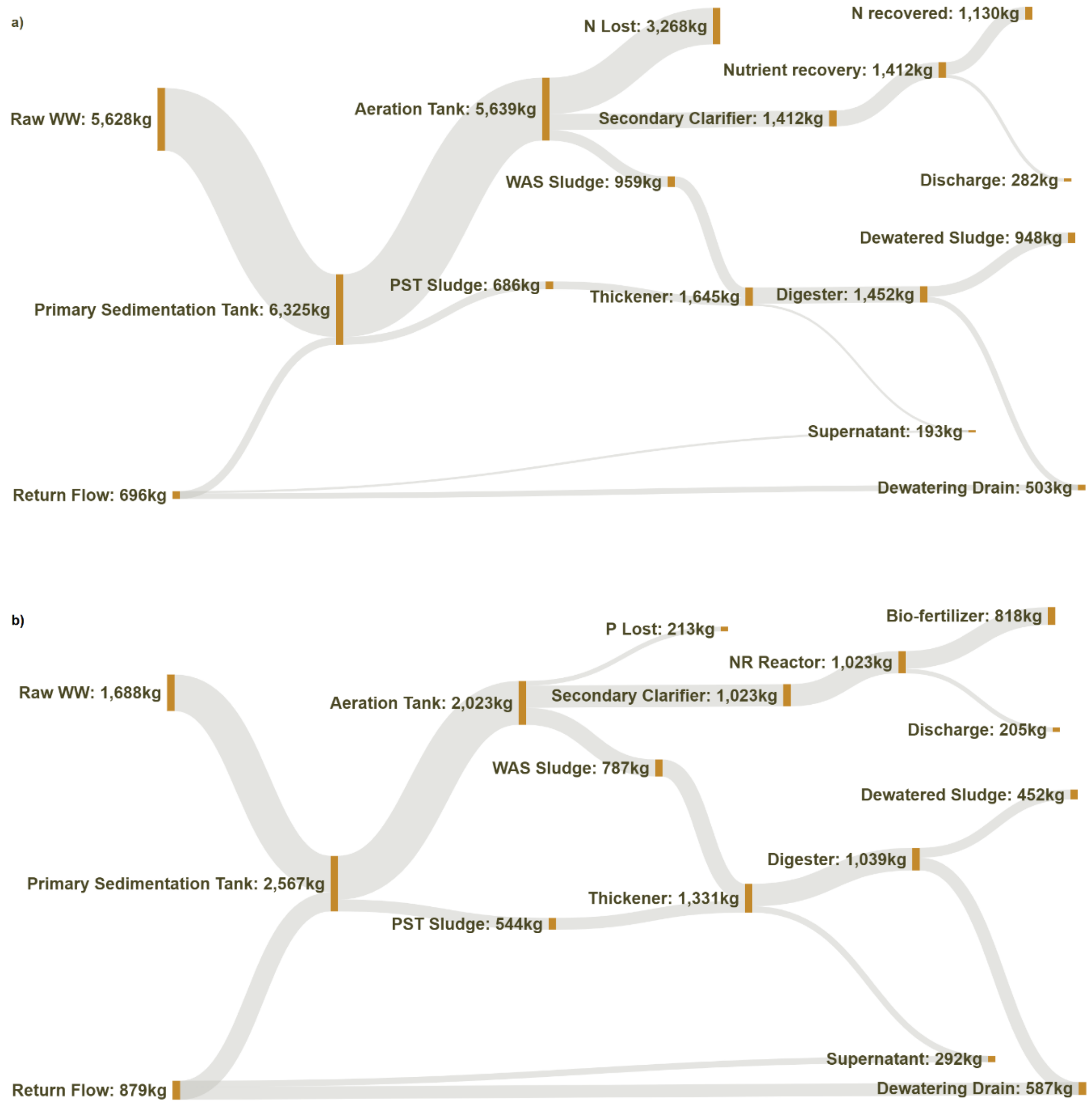
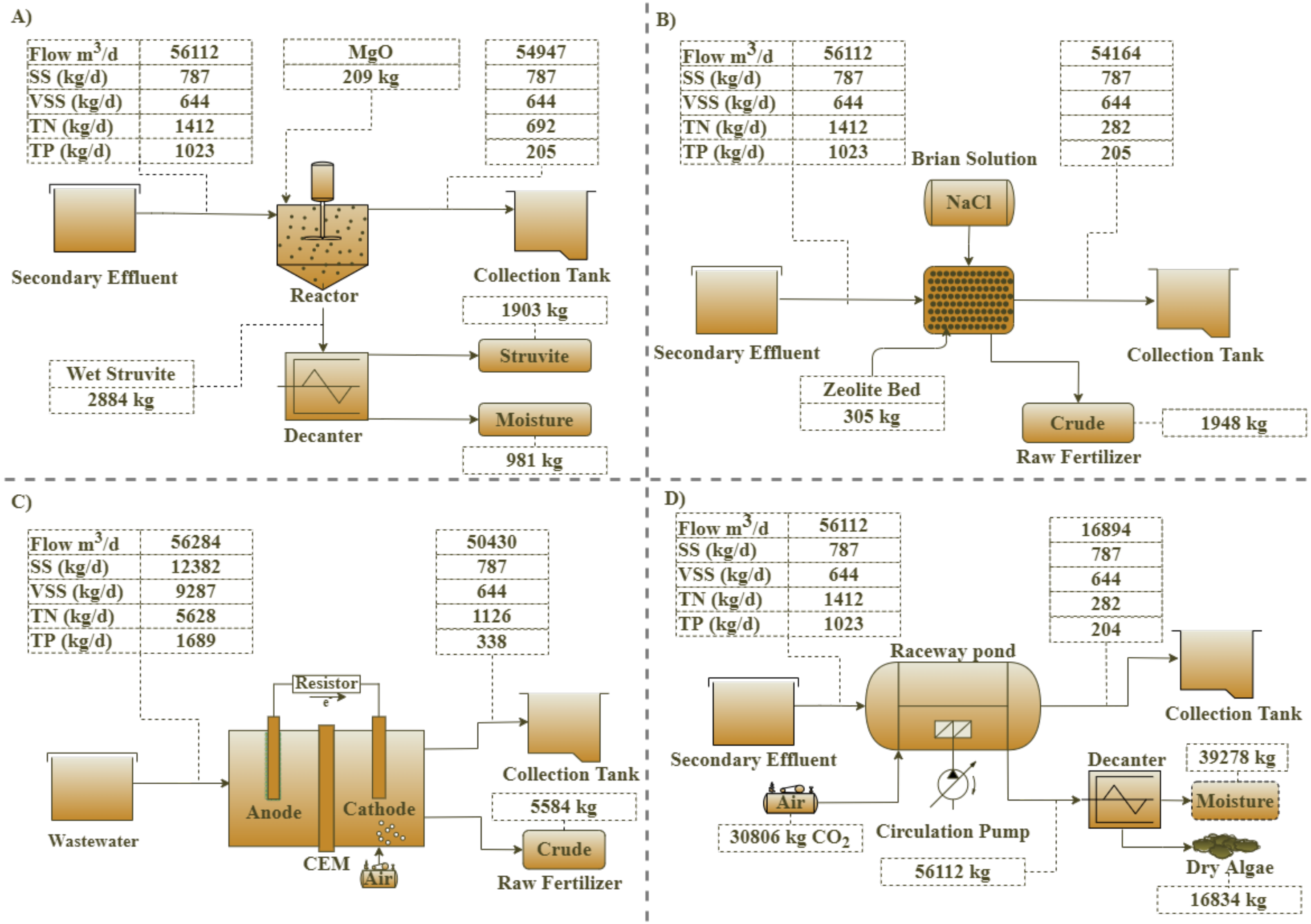

a)
Raw WW: 5,628kg
Primary Sedimentation Tank: 6,325kg
Return Flow: 696kg
Aeration Tank: 5,639kg
PST Sludge: 686kg
N Lost: 3,268kg
Secondary Clarifier: 1,412kg
WAS Sludge: 959kg
Thickener: 1,645kg
Nutrient recovery: 1,412kg
Digester: 1,452kg
N recovered: 1,130kg
Discharge: 282kg
Dewatered Sludge: 948kg
Supernatant: 193kg
Dewatering Drain: 503kg
b)
Raw WW: 1,688kg
Primary Sedimentation Tank: 2,567kg
Return Flow: 879kg
Aeration Tank: 2,023kg
P Lost: 213kg
Secondary Clarifier: 1,023kg
WAS Sludge: 787kg
PST Sludge: 544kg
Thickener: 1,331kg
NR Reactor: 1,023kg
Digester: 1,039kg
Bio-fertilizer: 818kg
Discharge: 205kg
Dewatered Sludge: 452kg
Supernatant: 292kg
Dewatering Drain: 587kg

Figure 2.

581



582

583 **Figure 3.**

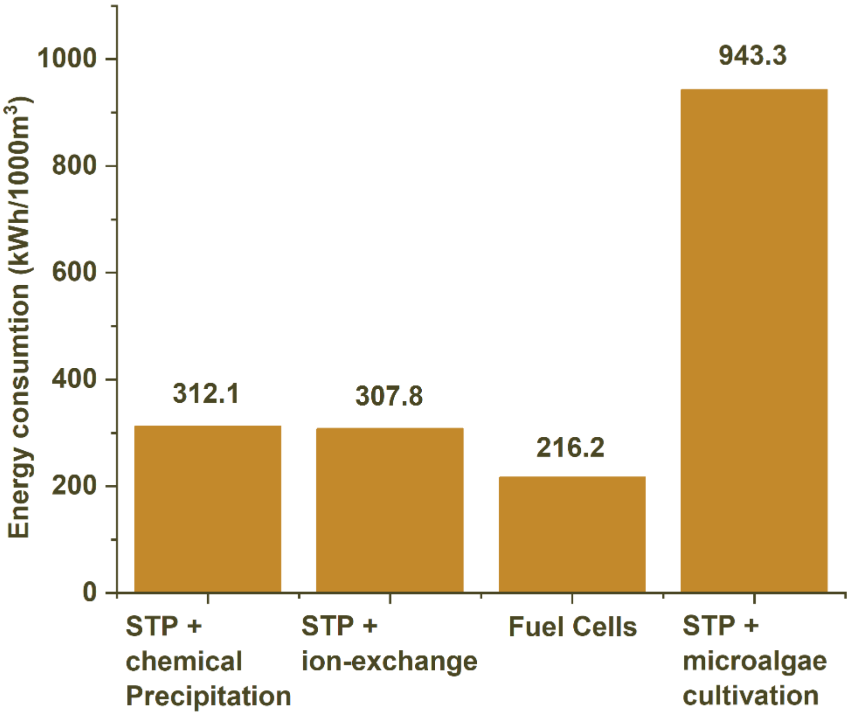
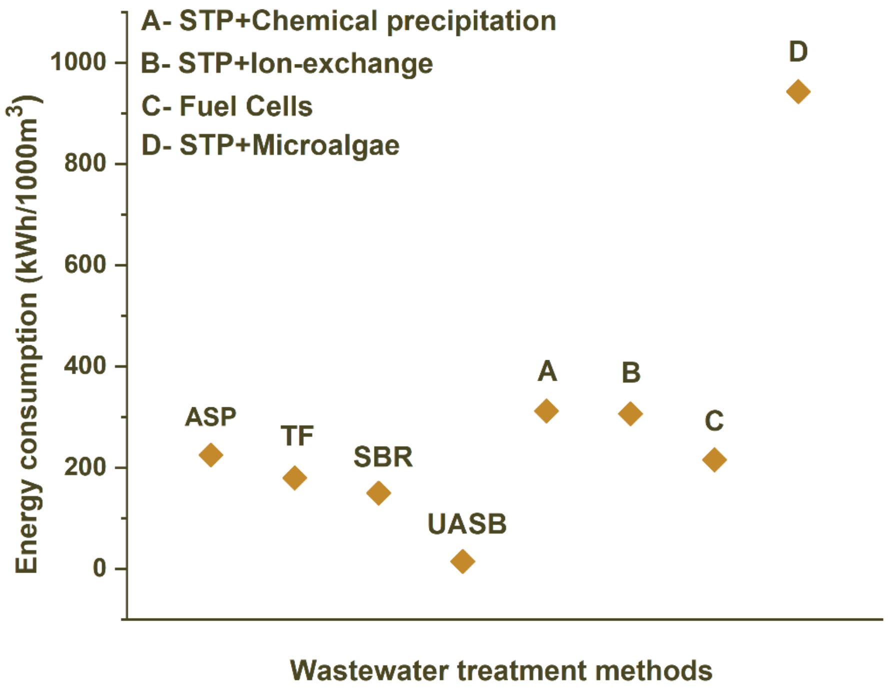

Energy consumtion (kWh/1000m3)
0
200
400
600
800
1000
312.1
307.8
216.2
943.3
STP + chemical Precipitation
STP + ion-exchange
Fuel Cells
STP + microalgae cultivation

Figure 4.



587

588 **Figure 5.**

Table 1.

Characteristics	Influent	Effluent	Tolerance limit
pH	6.5 – 9.0	5.5 – 9.0	5.5 – 9.0
BOD (mg/L)	400	30	100
SS (mg/L)	250	<20	200
TN (mg/L)	100	<10	NA
TP (mg/L)	30	<10	NA

Table 2.

Parameter	Value
Flow rate (m^3/day)	56284.83
Initial N concentration (mg/L)	100
Initial P concentration (mg/L)	30
N entering nutrient recovery system (mg/L)	≈40
P entering nutrient recovery system (mg/L)	≈18
Mg:P ratio	1:1
Nutrient uptake rate of zeolite (mg/g)	100
N recovery rate	80%
P recovery rate	80%

Table 3

Machinery	Energy consumption (kWh/d)	Energy consumption (kWh/1000m^3)	Energy consumption (%)
Pump 1 (Primary sedimentation tank to aeration tank)	88.94	1.50	0.5
Pump 2 (Aeration tank to secondary clarifier)	83.74	1.41	0.5
Pump 3 (Return sludge to primary sedimentation tank)	7.84	0.13	0.05
Aerator	5625	94.88	31.3
Thickener	8299	139.99	46.2
Anaerobic digester	946	15.96	5.2
Decanter	2200	37.11	12.2
Energy produced from biogas*	-193.6	-3.27	-1.1
Net consumption of electricity	**17056.92**	**303.05**	**100%**

*Negative sign indicates energy is produced.

Table 4.

Energy consumption (kWh/1000m^3)	Chemical precipitation	Ion-exchange	Microbial fuel cell	Microalgae cultivation
Pump (for pumping the WW to reactor)	1.55	1.5	1.5	1.45
Pump (for discharging the WW)	1.55	-	1.5	1.45
Pump (regeneration)		3.19	-	-
Agitator	6.04	-	-	-
Decanter	0.03	-	-	8.42
Aerator	-	-	213.2	533
Paddle wheel	-	-	-	6.39
Nutrient recovery	**9.1**	**4.7**	**216.2**	**640.3**
Energy consumption of STP	303.05	303.05		303.05
Total energy consumed	**312.1**	**307.8**	**216.2**	**943.3**

Table 5.

Method	Product	Physical state	Reactor Volume	Amount	Market price	Savings	Cost of chemicals used	Energy consumed	Cost of Energy	Net savings
(Unit)			(m^3)	(kg/1000m^3)	($/t)	($/1000$m^3$)	($/1000$m^3$)	(kWh/1000m^3)	($/1000$m^3$)	($/1000$m^3$)
Chemical precipitation	Struvite	Dry powder	7500	33.81	300	10.14	0.37	312.1	22.48	-12.33
Ion-exchange	Crude fertilizer	Liquid	7500	34.61	140	4.84	0.1	307.8	22.16	-17.31
Microbial fuel cell	Crude fertilizer	Liquid	15,000	104	140	14.56	-	216.2	15.57	-1
Microalgae cultivation	Microalgae	Dry powder	32,000	299.11	490	146.56	-	943.3	78.6	78.6