Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery: environmental and economic life cycle performance

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ABSTRACT

Although nutrient removal and recovery from municipal wastewater are desirable to protect phosphorus resource and water-bodies from eutrophication, it is unclear how much environmental and economic benefits and burdens it might cause. This study evaluated the environmental and economic life cycle performance of three different upgraded Processes A, B and C with commercially available technologies for nutrient removal and phosphorus recovery based on an existing Malaysian wastewater treatment plant with a sequencing batch reactor technology and diluted municipal wastewater. It is found that the integration of nutrient removal, phosphorus recovery and electricity generation in all upgraded processes reduced eutrophication potential by 62-76%, and global warming potential by 7-22%, which, however, were gained at the cost of increases in human toxicity, acidification, abiotic depletion (fossil fuel) and freshwater ecotoxicity potentials by an average of 23%. New technologies for nutrient removal and phosphorus recovery are thus needed to achieve holistic rather than some environmental benefits at the expense of others. In addition, the study on two different functional units (FU), i.e. per m^3 treated wastewater and per kg struvite recovered, shows that FU affected environmental assessment results, but the upgraded Process C had the least overall environmental burden with either of FUs, suggesting the necessity to use different functional units when comparing and selecting different technologies with two functions such as wastewater treatment and struvite production to confirm the best process configuration. The total life cycle costs of Processes A, B and C were 10.7%, 29.8% and 28.1%, respectively, higher than the existing process due to increased capital and operating costs. Therefore, a trade-off between environmental benefits and cost has to be balanced for technology selection or new integrated technologies have to be developed to achieve environmentally sustainable wastewater treatment economically.

Keywords: Wastewater treatment plants; Nutrient removal; Phosphorus recovery; Life cycle assessment; Life cycle cost; Functional units

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1. Introduction

With more concerns on eutrophication in natural water bodies, wastewater treatment plants (WWTPs) built for removals of only organic matter and suspended solids cannot meet the demand of environmental protection, particularly in nutrient-sensitive areas. Upgrading wastewater treatment plants for nutrient removal has been imperative in many areas. Nutrient removal, however, requires larger reactor volume, more energy and chemical consumption, and produces probably more chemically enriched sludge for disposal (Meneses et al., 2015). This might lead to a transfer of environmental impact caused by the nutrient in water to other environmental compartments such as air and soil. A holistic environmental assessment is, therefore, necessary for a selection of available technologies for upgrading and an evaluation of the overall environmental impact of the upgraded plants. Meanwhile, an economic assessment can provide information about affordability and price for environmental benefits (Garcia & Pargament., 2015). This is extremely important in developing countries with limited resource allocation for environment protection.

Eutrophication in Malaysia has reached a point where it cannot be ignored. According to Huang et al. (2015), 72% of rivers and lakes in Malaysia were in serious eutrophic conditions. But almost all existing WWTPs in Malaysia were not designed for nutrient removal. Therefore, upgrading WWTPs for nutrient removal in Malaysia has appeared inevitable in the future, just like what developed countries and some developing countries such as China have been doing. Malaysia is located in a tropical region with highly diluted municipal wastewater (Rashid & Liu., 2020) and many WWTPs, especially in large cities being operated with large capacity such as 500,000 population equivalent. Besides, a sequencing batch reactor (SBR) technology is widely adopted. With these features together, upgrading WWTPs and the environmental benefits and burdens it thus brings could be different from those in other regions. It should be pointed out that the selection of upgrading technology for nutrient removal should be based on the existing technology used for wastewater treatment to ensure the feasibility of upgraded technology and effective integration with existing facilities. Most of the previous research on technology selection via techno-economic and environmental assessment did not consider local factors such as wastewater characteristics, which might cause infeasibility of conclusions to a specific region. Furthermore, environmental assessment of WWTPs in developing countries is significantly less than developed countries as reported by Gallego-Schmid & Tarpani., 2019 and Zang et al., 2015, let alone environmental impact from the upgrading of WWTPs. Therefore, this study investigated the upgrading of a large and centralised WWTP with SBR technology and the selection of available technologies for nutrient removal and recovery from environmental and economic perspectives.

Various technologies with great potential to reduce chemical and energy consumption for nitrogen and phosphorus removal from municipal wastewater have been reported such as anammox, denitrifying phosphorus removal (DPR), and reverse/forward osmosis membrane filtration, but almost all of these are still at research stage without application(Third et al., 2005; Haiming Zou et al., 2014; Hube et al., 2020), Anammox is a novel/cost-effective way to reduce nitrogen in ammonium-rich wastewater (Hauck et al., 2016;), but not applicable to diluted municipal wastewater. DPR can remove phosphorus and nitrite/nitrate simultaneously with limited chemical oxygen demand (COD) and reduced aeration, but it demands complicated control without practical application so far (Jin et al., 2017). Some variants of existing mature technologies such as integrated fixed-film activated sludge process (Waqas et al., 2020), and sequencing batch membrane photobioreactor seem more promising for rapid full-scale application (Lau et al., 2019; Sheng et al., 2017)In practice, nitrogen removal from municipal wastewater still relies on biological nitrification and denitrification while phosphorus removal depends on either enhanced biological phosphorus removal (EBPR) or chemical precipitation by aluminium, ferric or calcium salts. EBPR is more environmentally friendly without or with little chemical consumption, but it has relatively lower phosphorus removal efficiency and less performance stability compared with chemical precipitation. Conventional chemical phosphorus removal demands chemicals to precipitate phosphate in wastewater, producing more chemically enriched sludge for disposal. Both technologies are widely used in practice. It is thus not surprising that to upgrade WWTPs for nutrient removal, nitrification/denitrification for nitrogen removal, and EBPR or chemical precipitation (Maurer & Boller., 1999) for phosphorus removal have to be adopted. More recently, a new technology called aerobic granular sludge technology has been reported to have good nutrient removal efficiency due to the co-existence of aerobic, anoxic and anaerobic zones in granules (Piotr & Cydzik-kwiatkowska., 2018; Liu et al., 2010). A full-scale aerobic granular sludge process for sewage treatment has demonstrated that total nitrogen and phosphorus concentrations can be reduced to 7 mg/L and 1 mg/L, respectively, without chemical dose in normal conditions (Pronk et al., 2015). More importantly, aerobic granule technology is based on SBR operation, which enables retrofitting of existing WWTPs with SBR technology to granular sludge SBR relatively easy by changing operational conditions. More than 60 successful full-scale application of aerobic granular sludge-SBR technology allows itself to be one of the feasible options to upgrade especially SBR based plants in Malaysia.

With the concern of phosphorus depletion within the next 50 to 100 years (Cordell et al., 2009), wastewater has been considered as one of the important phosphorus sinks for phosphorus recovery (Egle et al., 2016). Sweden, for example, has required that 60% of phosphorus in municipal wastewater needs to be recovered for phosphorus security (Hultman et al., 2004). Apart from the direct application of stabilised sewage sludge to land for nutrient recovery, some technologies have been developed to recover phosphorus from sludge to make phosphorus products such as slow-releasing fertiliser struvite (Corre et al., 2009) or calcium phosphate (Woods et al., 1999) to supplement rock phosphate. Most successfully commercialised phosphorus recovery technologies are Ostara from Canada, Gifhorn and Airprex from Germany, and Unitika from Japan. Phosphorus recovery cannot only recover phosphorus resource but also alleviate pipe and pump clogging problems caused by uncontrolled struvite crystallisation and deposition in the sludge digestion and downstream treatment processes (Urdalen, 2013). Thus, phosphorus recovery could be an option to WWTPs which need upgrading. Although upgrading WWTPs seems still too costly in developing countries, it would be beneficial to see how much environmental and economic benefits or burdens it could bring when upgrading WWTPs for nutrient removal and recovery.

Currently, environmental assessment using life cycle assessment is believed as a useful analytical tool to develop a metric with which to compare, and evaluate processes and products with regards to their potential environmental effects from the cradle to the grave (Hauschild et al., 2013). Thus it could be used effectively to guide technology and process selection. The economic cost, another important factor to consider for WWTP upgrading, has been increasingly conducted using life cycle costing assessment to select wastewater treatment solutions or processes (Rawal & Duggal., 2016; Hernandez-Sancho et al., 2010). Both environmental impact assessment and economic analysis can provide comprehensive information as guidelines to decision-makers for upgrading WWTPs from both financial and environmental perspectives.

This study thus aims to design upgrading processes based on an existing Malaysian centralised wastewater treatment plant with SBR technology for nutrient removal and resource recovery, and to assess economic burdens and environmental benefits or burdens of upgraded processes with life cycle assessment. All selected technologies for upgrading are commercially successful in ensuring the practical feasibility of upgraded processes. Phosphorus recovery as a possible option in the future was also considered to investigate net environmental benefit. The ultimate goals of this study include the development of general guidelines for upgrading WWTPs for nutrient removal or phosphorus recovery and the provision of comprehensive information to decision makers for upgrading.

2. Materials and methods

2.1 The selection and description of the case study

A large and centralised municipal Malaysian sewage treatment plant (STP) in Penang, Malaysia, was selected for upgrading to remove nutrients and recover phosphorus to improve the local environmental status and phosphorus security. Malaysian STP treated an average flow rate of 148,950 m^3/d domestic wastewater from a separate sewer system to serve 662,002 population equivalent in 2017. The existing Malaysian STP mainly consists of grit and grease screening as primary treatment, 4 SBRs for a combined primary sludge settling and chemical oxygen demand (COD) removal, gravity belt thickener for sludge thickening, anaerobic digester for sludge volume reduction, and biosolids dewatering for final sludge landfilling (**Figure 1**). Three high-strength streams produced from sludge pre-holding tank, sludge thickening tank and centrifuge decanter for dewatering are returned to SBRs for treatment. The treated water is discharged into the river nearby, while the sludge produced is sent to a landfill located 47 km away. This type of SBR based WWTPs is widely used in Malaysia and is considered as a typical wastewater treatment plant. The infrastructure of Malaysian STP was built in 2007 and is expected to have a 40 to 50-year lifetime as suggested by (Ruhland et al., 2006).

2.2 Sampling and analytical methods

The data of process, operation, and quality of influent and effluent in Malaysian STP were provided by the plant manager. To supplement any necessary data for this study especially on the mass balance calculation, additional samples at 4 different points, i.e. the influent to the treatment plant, the immediate inlet to SBR after mixing with side stream from sludge treatment units, the inlet to the sludge treatment units and the effluent to the environment, were taken and analysed in August 2017. Glass bottles were used to collect and store the samples from all four sampling points. All samples were labelled and kept cold inside iceboxes at 4^{o}C during collection, and then transported to the laboratories for analytical determination by the analytical team from the National University of Malaysia (UKM). Total biochemical oxygen demand ($TBOD_5$), total chemical oxygen demand (TCOD), total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) were analysed following standard methods by American Public Health Association (APHA). While nitrate and sulfate were measured using HACH method (i.e. HACH 8171). The data from these 4 sampling points can be used not only to validate the methods used for mass balance in the existing STP, but also to conduct mass balance in the three upgraded processes.

2.3 Design of the three upgraded processes

The existing wastewater treatment process is shown in **Figure 1**. SBRs play dual roles for both primary sludge settling and biological COD oxidation. Apart from 1-hr filling, 1-hr settling and 1-hr decanting, only 1-hr aeration is used to oxidise COD, making the total cycle time as 4 hours. 4 SBRs with each reactor working volume of 6206 m^3 are being operated alternatingly to deal with 148,950 m^3 municipal wastewater per day continuously. The characteristics of municipal wastewater to this plant are shown in **Table S1.** Based on local wastewater characteristics and SBR technology adopted in the existing Malaysian STP, three new processes denoted as Process A, Process B and Process C, respectively, were designed by adopting commercially available technologies to upgrade the existing plant for nutrient removal and phosphorus recovery. One important criterion for the upgrading design is to minimise the retrofitting requirement and meanwhile to make the best use of the existing facilities to maximise the integration. Processes A and B adopted nitrification and denitrification for nitrogen (N) removal with extended cycle time of SBRs. Process A relied on enhanced biological phosphorus (P) removal (EBPR), while Process B used ferric precipitation to remove phosphorus. Process C adopted aerobic granular sludge technology for simultaneous biological N and P removal.

Commercial technologies, i.e. AirPrex and Gifhorn, were chosen for phosphorus recovery with AirPrex for P recovery in Process A and Gifhorn in Processes B and C. It is assumed that 22% and 40% of TP with respect to sludge input was recovered by Airprex (Kabbe, 2015) and Gifhorn (Egle et al., 2016), respectively. Airprex forms struvite by stripping out CO_2 and adds $MgCl_2$, and installed between the anaerobic digester and dewatering equipment. The process converts orthophosphate into struvite crystals which are harvested from the bottom of the reactor, i.e. sand washer (Niewersch & Stemann., 2014; P-Rex Factsheet, 2015). In Gifhorn, phosphorus bound in the biomass is extracted from the solid phase of digested sewage sludge by the addition of sulfuric acid (H_2SO_4). In a second step, the dissolved heavy metals are precipitated as sulfides (dosing of Na_2S) by adjusting pH with NaOH, to minimise the co-precipitation of heavy metals with fertiliser products in the subsequent step for phosphate precipitation. After solid/liquid separation with a decanter, dosing of $Mg(OH)_2$ initiates precipitation of phosphorus as a mix of struvite/calcium phosphate (adjusted with NaOH). The P product is harvested by a second solid/liquid separation (P-Rex Factsheet, 2015).

2.4 Mass and energy balances

The mass balance of the existing and the three upgraded processes was calculated based on flowrate, TCOD, TN, TP, and suspended and volatile suspended solids (SS and VSS) to generate balancing inventory data in water and sludge streams, respectively. The plant-wide mass balance started from influent to WWTP and ended with effluent to rivers, and sludge to landfill. An iterative procedure was developed in an excel spreadsheet for the main interrelated parameters to carry out the mass balance calculation. The first iteration from the initial flow rate determined return flow rates, which affected the flow rate of the stream into SBRs. From here, the second iteration started. Iteration was stopped until the incremental changes in flow quantities of carbon and nutrients in return flows were less than 5%. The validity of the iterative procedure developed was verified with the sampled data from the existing process. The equations for mass balance calculations are shown in **Table S6**.

The calculation of energy balance for all upgraded processes was carried out based on the energy consumption in the existing process and the additional energy consumption for nutrient removal, phosphorus recovery and electricity recovery (**Table 2**). The electricity consumption for blowers and P recovery is shown in **Table S3**. Electricity consumption for P recovery process was calculated based on the average total electricity demand suggested by P-Rex Factsheet, 2015. It is assumed that Airprex and Gifhorn require 10.3 kWh/1 kg P recovered and 6.9 kWh/1 kg P recovered, respectively (P-Rex Factsheet, 2015). Electricity production from the sludge anaerobic digestion and CHP were calculated in the three upgraded processes with the assumption of 40% electricity recovery efficiency from CHP.

2.5 Environmental assessment

The environmental assessment was performed by a life cycle assessment (LCA) using SimaPro v9.0. International standards and recommendations by ISO, 2006 were followed.

2.5.1 Goal and scope

The goal was to carry out a comparative assessment of LCA to evaluate the environmental benefits/burdens of the three newly upgraded processes, which can be used as options for the upgrading of WWTP to remove nutrients and recover phosphorus. ‘Cradle to grave’ analysis was adopted which began with the construction and ended at the demolition stage. In the operation stage, wastewater flowrate, pollution loads, transportation of chemicals and sludge, energy consumption and chemical consumption were considered. In the construction stage, materials (e.g. steel, concrete and timber) and energy used for the construction of all operation units were considered. While in the demolition of operation units and buildings, steel recycled and energy used were considered (Hao et al., 2019). Also, the avoided products such as struvite and electricity recovered from the upgraded processes of Malaysian STP were included, but the impact from struvite application as fertiliser was not considered. The illustrated system boundary for this LCA - WWTP study is shown in **Figure 1.**

2.5.2 Functional units

1 m^3 of treated wastewater was used as functional unit 1 (FU1) to compare the environmental impacts between the upgraded processes and the existing process. FU1 was widely adopted for LCA in WWTPs with/without nutrient removal and recovery (Piao et al., 2015; Lorenzo-Toja et al., 2016; Hauck et al., 2016; Coats et al., 2011; Niero et al., 2014). The results based on FU1 could thus be easily compared with LCA studies from the literature. Using per m^3 of treated wastewater as a functional unit, however, is believed not to be able to well reflect wastewater treatment performance especially for nutrient removal and recovery (Pradel et al., 2016). The primary functions to achieve in the upgraded processes in this study are to remove nutrients and to recover phosphate as fertiliser (struvite) from sludge. Therefore, the functional unit defined as 1 kg of struvite recovered ($NH_4MgPO_4.6H_2O$) was used as FU2 as well (Amann et al., 2018; Pradel & Aissani., 2019) to assess the environmental efficiency of per kg struvite recovered between the three upgraded processes. In this way, we could estimate how much environmental benefits/burdens were generated for per kg struvite recovered.

2.5.3 Life cycle inventory (LCI)

The operation data provided by the plant managers and the data from sampling in August 2017 in Malaysian STP were used as the basic inventory data. Specifically, the life cycle inventory (LCI) consists of the following parameters: 1) inputs of resources including electricity consumption for aeration, pumping, stirring; transportation for sludge disposal; chemical consumption for wastewater treatment and sludge treatment; 2) the volume of wastewater treated, influent and effluent characteristics such as influent and effluent TCOD, TN, TP, VSS, SS, and sludge quantity; 3) emissions of gases such as carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O) from the operation of the plant as outputs. Direct N_2O was mainly generated from biological nitrogen removal process and CH_4 was from anaerobic wastewater and/or sludge treatment (Masuda et al., 2015); gas emissions were calculated according to the Intergovernmental Panel on Climate Change guidelines (IPCC, 2006) based on the 100-year time horizon; 4) construction inputs such as steel, timber, concrete and energy consumption; 5) demolition inputs after lifespan such as energy consumption, where data for the construction and demolition process were calculated by using the method provided by Hao et al., 2019; 6) avoided products including electricity and struvite recovered in the operation phase, and steel recovered in the demolition phase. All inventory data are provided in **Table S4** for FU1 and in **Table S5** for FU2. Background data were obtained from the Ecoinvent v3.3 database as described below:

a. Electricity production in Malaysia was selected from the Ecoinvent v3.3 database.

b. Chemical production: Data on the production of chemicals (e.g. methanol, iron chloride, magnesium chloride, sulphuric acid, sodium sulfide, sodium hydroxide, magnesium hydroxide, and polymers), were selected from the European life cycle database (ELCD) and Ecoinvent v3.3 database. For polyelectrolyte for sludge dewatering, a similar production process for acrylonitrile was taken from the Ecoinvent v3.3 as proposed by Rodriguez-Garcia et al., 2011.

c. Lorries with a capacity of 3.5-7.5 metric ton were selected as transport vehicles for the disposal of sludge produced from Malaysian STP, as well as for the chemical transportation to the site.

d. Inputs for construction: Data of the resources such as steel, timber and concrete were selected from the Ecoinvent v3.3 database.

2.5.4 Life cycle impact assessment (LCIA) and interpretation

Life cycle impact assessment (LCIA) was conducted with the characterisation factors from CML-IA (baseline v3.04) methodology (Mbaya et al., 2017; Ruhland et al., 2006) to compare the environmental footprints of the existing and the three upgraded processes. As wastewater treatment plants mainly generate climate change-related impacts and environmental quality issues (Renou et al., 2007), six midpoint characterisation impact categories such as eutrophication potential (EP), freshwater ecotoxicity potential (FEP), human toxicity potential (HTP), global warming potential (GWP), abiotic depletion (fossil fuel) potential (ADFP) and acidification potential (AP) were chosen as the main assessment categories. Since concentrations of heavy metals in sludge were not available in the three new processes, terrestrial ecotoxicity impact was not included in the assessment. The LCA results were finally interpreted to assess the contribution of each component in the inventory of each environmental impact category. Besides, the normalisation factors from World 2000 in CML-IA method were used for the normalisation of the environmental impact categories at the midpoints based on per person per year.

Upgraded Malaysian STP is expected to have a 40-year lifetime. In the next 40 years of operation of Malaysian STP, there will be variation in the mass load of pollutants which could affect the electricity consumption, chemicals consumption and nutrient concentration in the effluent. Sensitivity analysis was thus conducted to evaluate how the variations in inventory data such as electricity consumption, nutrient concentrations in effluent and chemical consumption affect LCA impact category results with 20 and 40 years of design life. ±10% variation of inventory data for 20 years was selected to measure the variability of environmental impact results in half-life of the upgraded STP. While ±20% variation of inventory data for 40 years was selected to measure higher variability of environmental impact results in the whole lifetime of the upgraded STP. In this way, the effects of the accuracy of inventory data of wastewater treatment plant with a long design life were evaluated. FU1, i.e. per m^3 treated wastewater was selected for this analysis to facilitate the comparison with the results from other studies. However, the effect from construction and demolition were not included in the sensitivity analysis because their inventory data are the same throughout the whole lifetime of upgraded Malaysian STP.

2.6 Hotspot analysis of electricity consumption

Energy consumption was used to identify hotspots because it is the main contributor during the operation of WWTP to many environmental impact categories (i.e. GWP, ADFP, HTP and AP). Hotspot analysis was conducted to check how much that nutrient removal and phosphorus recovery in the existing and upgraded processes could contribute to the total electricity consumption. Power consumption data from each electric device in water and sludge line of the existing plant (i.e. pumping, bar screen, aeration and mechanical dewatering) was provided by the plant. The data of energy required in the newly designed processes such as for struvite recovery and the nutrient removal in SBRs were obtained from the energy balance.

2.7 Economic assessment

The economic cost of different processes during construction and operation periods was assessed. Life cycle cost (LCC) based on per population equivalent (PE) per day was calculated by **Equation 1** according to Awad et al., 2019. Per PE was used as a functional unit in LCC assessment as WWTPs are designed, constructed and operated based on PE. The prices of materials (i.e. steel, concrete or timber), transport, disposal fee and electricity were obtained from the current Malaysian market (2017-2019). For the construction cost, additional items for the upgrading processes were considered, i.e. new reactor cost, CHP generator, extra blower, Airprex reactor and Gifhorn reactors. The operation cost for P recovery process was assumed as 9.0 USD/1kg P recovered for Airprex, and 17.8 USD/1 kg P recovered for Gifhorn (Egle et al., 2016). Prices for chemicals were referred to the literature values by Lorenzo-Toja et al., 2016a; Awad et al., 2019; Bertanza et al., 2014. 1 kWh of electricity in Malaysia costs 0.15 USD (United States dollar). Labour cost varies over time and it also depends on the plant location (Awad et al., 2019). Since the comparative assessment in this study is for the existing process and the three upgraded processes at the same plant during the same operation period, labour cost was not considered in this study. To get the net life cycle costs, the revenues from the recovered products such as electricity and struvite from the operation were deducted.

$$\text{LCC (USD / PE·day)} = CC + OC + TC - S \qquad \textbf{Equation 1}$$

Where:

LCC = Total life cycle cost

CC = Construction cost

OC = Operation cost (i.e. electricity consumption, chemicals and landfill disposal fee)

TC = Transport cost (for sludge and chemicals)

S = Revenue from the recovered products such as electricity and phosphorus

3. Results and discussion

3.1 Design of three upgraded processes for nutrient removal and phosphorus recovery

3.1.1 Design of three upgraded processes for nitrogen and phosphorus removal

To achieve nitrification, denitrification and EBPR, the cycle time of SBR was extended to 6 hours in upgraded Process A to accommodate anaerobic/aerobic/anoxic (AOA) phases with a ratio of anaerobic: aerobic: anoxic as 1:2:1 (Liu et al., 2013). Soejima et al. (2008) showed that with an insufficient carbon source, nitrogen removal rate in AOA-SBR system was only 34%. Therefore, external carbon sources such as methanol were suggested to be dosed in the anoxic period to improve total nitrogen removal efficiency. Due to the extension of cycle time, the plant's treating capacity was reduced, and 2 more SBRs with the same reactor volume were needed to deal with the same treating capacity of the plant after upgrading. Meanwhile, extra aeration is needed for nitrification on the top of COD oxidation.

Chemical precipitation is widely used in WWTPs for phosphorus removal, thus, in the upgraded Process B, biological nitrogen removal and ferric precipitation were adopted. A typical phase ratio of aerobic to anoxic as 2:1 was selected (Liu et al., 2013). The aeration phase was extended for nitrification. To make the continuous operation of SBRs in the upgraded Process B easier, the cycle time was kept at 6 hours with additional 2 SBRs to deal with the same plant treating capacity. Similar to Process A, methanol was dosed in the anoxic period for denitrification. Aerobic granular sludge technology was adopted in the upgraded Process C with the aeration phase extended from 1 hour to 2 hours for simultaneous nitrogen and phosphorus removal, resulting in 5-hr total cycle time. Thus 1 more SBR in the upgraded Process C was added. The cyclic operation of SBRs in the three upgraded processes with nutrient removal is shown in **Figure S2**.

3.1.2 Addition of extra units for phosphorus recovery in three upgraded processes

To provide an alternative phosphorus source to the agriculture and to alleviate pipe and pump clogging caused by uncontrolled struvite formation, P recovery from wastewater was integrated into Processes A, B and C. AirPrex technology was selected in the upgraded Process A due to its low chemical demand, low investment cost and applicability to sludge from the biological phosphorus removal process. In Process C, phosphorus could be removed by a combined EBPR and biologically induced phosphorus precipitation in aerobic granules (Manas et al., 2011; Manas et al., 2012). Gifhorn technology was, therefore, chosen due to its applicability to both EBPR and chemically precipitated phosphorus, high technical maturity and P recovery potential (Egle et al., 2016). For Process B, since phosphorus mainly exists in the form of chemical precipitate, Gifhorn technology was used for upgrading.

In the Gifhorn process, sludge from anaerobic digesters was digested first by adding 98% sulfuric acid at a pH of 4.5 to release metals and phosphorus. In the second step, the dissolved heavy metals were precipitated as sulfides by dosing sodium sulfide at pH 5.6 which was adjusted by sodium hydroxide, $Na(OH)_2$. After the solid and liquid separation by a decanter, magnesium hydroxide was dosed into the liquid stream in the second Gifhorn reactor at a pH of 9.0 adjusted by $Na(OH)_2$ for struvite crystallisation. The chemical consumption for each process for nutrient removal and recovery is shown in **Table S2**. Phosphorus recovery with either Airprex or Gifhorn is optional as additional units to integrate with upgraded three processes for nutrient removal. It is worth assessing how much environmental and economic burdens that phosphorus recovery could bring and comparing them with the benefits from it.

3.2 Mass and energy balances of the existing process and three upgraded processes with nutrient removal and phosphorus recovery

3.2.1 Mass balance of the existing and three upgraded processes

Based on the upgraded processes in **Figure 2**, mass balance was conducted and the mass flow of each stream is labelled in **Figure S1** for all three upgraded processes. Water quality parameters are shown in **Table S1**. With the addition of nutrient removal operation, total nitrogen and phosphorus removal efficiencies increased in the upgraded Processes A, B and C by 47% and 37% on average, respectively, compared with the existing process (**Table 1**). Whilst the removal efficiency of TSS and TCOD remain 92% and 90%, respectively, after the upgrading, similar to those in the existing process because the operation for TSS and TCOD removal were not changed by upgrading. In comparison with 15 mg/L TN and 1.05 mg/L TP in the effluent of the existing process, process C with aerobic granular sludge (AGS) achieved the best effluent quality with concentrations of TN and TP at 3.2mg/L and 0.06mg/L, respectively, due to its better treatment performance (Pronk et al., 2015; Chen et al., 2015). Piotr & Cydzik-kwiatkowska. (2018) also reported that the upgraded WWTP based on AGS in Poland achieved 87% of TN and 95% of TP removal efficiencies. Process A with activated sludge has the highest effluent concentrations, i.e. 5.4mg/L of TN and 0.24mg/L of TP. A potential reason could be the P release at anoxic condition, which is not easily resolved (Qiu & Ting., 2014; Zhou et al., 2016). But all three processes achieved satisfactory treatment performance in terms of nutrient removal.

For sludge production, the produced dry-weight sludge decreased by 24% on average in all three upgraded processes compared with the existing process, mainly due to the extended aeration used for nutrient removal as the extended aeration can reduce sludge (**Table 1**). In Process B, the increased sludge from ferric phosphate precipitate is less than the decreased sludge from extended aeration, resulting in a net sludge reduction by 22% compared with the existing process. One of the important reasons for this is that the influent was very low, i.e. 2.6 mg/L, which resulted in little inorganic phosphorus precipitate.

The production of struvite from 3 upgraded processes is shown in **Table 1**. It can be seen that Processes B and C based on Gifhorn produced much more struvite while recovered struvite from Process A with Airprex is only 60% of that from Processes B and C. As pointed out by Amann et al. (2018), P recovery potential of AirPrex process is 10%-22% with respect to WWTP influent, is relatively low compared to that of Gifhorn which can be up to 55%. However, when P recovery cost is considered, AirPrex process is cheaper with lower investment and less chemical demand (Egle et al., 2016). For instance, the cost of 1kg P recovered from Gifhorn process is up to 16€ (≈ 18.3USD) which is almost twice as that from AirPrex process (Egle et al., 2016). Therefore, it is necessary to look into the net costs of both technologies.

3.2.2 Energy balance of the existing process and three upgraded processes

The energy consumption in all processes is mainly from aeration, stirring in digesters and pumping fluids between different units. The energy consumption and generation from all processes are shown in **Table 2**. The total electricity consumption for secondary treatment in the upgraded processes increased by 30-34% compared with the existing process (at 18,121kWh/day), which is due to the increased energy consumption for nitrification in SBRs as removal of per g nitrogen demands 4.6 g oxygen. Addition of phosphorus removal units incurred more electricity consumption although P recovery only accounts for 2-3% of the total electricity consumption in the plant. With conventional nitrification/denitrification, it is unavoidable that nutrient removal is achieved at the expense of higher capital and operational costs. This highlights the importance of developing less energy-intensive nitrogen removal technology such as Anammox for mainstream nitrogen removal or high efficient energy recovery technology.

Considering more energy is consumed for nutrient removal, the implementation of sludge digestion and CHP for electricity production is imperative to alleviate carbon emission by reducing net electricity consumption per day in WWTPs. In addition, renewable energy production from sludge can improve the security of energy supply from WWTPs. The net electricity consumption in Process A and B was reduced by 3.1% and 3.6%, respectively, while it increased by 0.8% in Process C compared with the existing process due to its high electricity consumption per day mainly by the secondary treatment. In general, the recovered electricity from sludge just offset the energy used for nutrient removal, allowing equivalent net electricity consumption after upgrading.

3.2.3 Hotspot analysis of existing process and the three upgraded processes in terms of electricity consumption

Two wastewater treatment scenarios, i.e. scenario 1 with nutrient removal only (**Figure S3a**) and scenario 2 with both nutrient removal and phosphorus recovery (**Figure S3b**), were considered to estimate electricity consumption for wastewater treatment in each process including primary treatment (screening and grid removal), secondary treatment (COD or COD and nutrient removal), sludge treatment and phosphorus recovery. In the existing process, the electricity consumption in the secondary treatment (SBR) process accounted for 59.2% of the total energy consumption due to intensive energy use for aeration in SBRs. This result is within the range in the study by Mininni et al. (2015) who estimated the electricity consumption for aeration in ten case studies mainly with modified ludzack ettinger (MLE) activated sludge process was within 43-60% of total electricity consumption. Gu et al. (2017) also reported in their study that the aeration process contributed to 60% of energy use in conventional activated sludge (CAS) wastewater treatment plant in China. In the three upgraded processes with nutrient removal, the distribution of energy consumption by SBRs was almost the same, i.e. at around 67% which was higher than the existing process due to nitrification. There was almost no significant difference among the upgraded processes regarding electricity contribution from primary-treatment, secondary treatment, sludge treatment, and with/without P recovery because of similar technologies used for COD and nitrogen removal which are the primary energy consumers.

As shown in **Figure S3a** and **Figure S3b**, the electricity contribution in the secondary treatment increased from 59% in the existing process to 65-68% in the upgraded processes in both scenarios with/without P recovery. Although electricity was recovered in the upgraded processes, electricity still accounted for 2/3 of the total electricity, even higher than the existing process without electricity generation. Although pre-treatment units were the same before and after upgrading, the percentage of electricity consumption for pre-treatment and sludge treatment in the upgraded processes reduced by around 3% and 5%, respectively, compared with the existing process because of more electricity consumed for nutrient removal. In addition, the comparison between two scenarios with and without P recovery showed that introducing P recovery units, either AirPrex or Gifhorn, only contributed less than 2.5% of electricity. These comparisons indicate the importance of developing energy-saving nutrient removal technologies to replace conventional biological nitrification for reduced energy consumption and/or to enhance energy recovery from wastewater to cover more electricity consumed for nutrient removal.

3.3 Environmental impact analysis of the existing process and the three upgraded processes with nutrient removal and phosphorus recovery

The purpose of upgrading the existing process is to improve effluent quality and recover resources such as energy and phosphorus from wastewater to enhance environmental protection. To assess the holistic environmental benefit, environmental impact analysis with LCA was carried out to guide the selection of newly designed processes. As shown in **Figure 3**, it can be seen that except for eutrophication potential, the environmental impact was largely derived from the operation of treatment plants. Construction and demolition only contribute less than 10% in each impact category for all four processes. A similar finding was reported by Foley et al. (2010) and Hao et al. (2019) that the operation of WWTP contributed more than 90% to environmental impact categories compared with construction and demolition phases. The only environmental benefit in the existing process was from steel recycling in the demolition phase with -7.5% in HTP, and -1.2% in ADFP and GWP, respectively.

In the existing process, electricity consumption contributes 57-95% to five environmental impact categories namely human toxicity potential (HTP), acidification potential (AP), abiotic (fossil fuel) depletion potential (ADFP), freshwater ecotoxicity potential (FEP) and global warming potential (GWP), while eutrophication potential (EP) is mainly from effluent discharge. In the upgraded processes, it is found that electricity recovery benefited the environmental impacts in all six categories particularly in GWP, with an average of 19% reduction. To increase energy recovery, Adsorption-Biological (A-B) process could be used for more capture of carbon (Jonasson, 2007). But for SBRs in this study, it is less likely to upgrade process to A-B process. The upgrading solutions are restricted by the current technology used in the existing plant.

The upgraded processes had additional demand for chemicals for denitrification, phosphorus precipitation and phosphorus recovery to produce struvite, causing additional environmental burdens to all environmental categories except eutrophication. The Process B had the highest chemical consumption due to the consumptions of ferric chloride for phosphorus precipitation, methanol dose for denitrification, as well as sulphuric acid, sodium hydroxide, sodium sulfide and magnesium chloride for P recovery, leading to the highest environmental impact. The chemical contribution to ADFP in Process B reached 28%, the second-highest contributor after electricity. Simultaneous nitrification and denitrification, and the combined EBPR and biologically induced phosphorus precipitation in aerobic granular sludge in Process C required no chemicals for nutrient removal (Piotr & Cydzik-kwiatkowska., 2018; Pronk et al., 2015), making it the most promising technology to upgrade the existing SBR plants for wastewater treatment.

Resource recovery from three upgraded processes created environmental benefits in all six environmental impact categories. For instance, the recovery of electricity and phosphorus from the operation, and steel recycled from demolition contributed up to 19% in GWP. P recovery alone, however, only provided 2-5% environmental benefits by reducing rock phosphate mining. The small net environmental benefit brought by P recovery is also partly due to low P recovery efficiencies accompanied by large amounts of energy and chemical input for nutrient removal (Pradel & Aissani., 2019). The other reason is low influent phosphorus concentration in Malaysian STP at around 2.6 mg/L. The environmental benefit of phosphorus recovery could increase with the increase in influent phosphorus concentration. Therefore, it needs to be careful to consider building phosphorus recovery units in WWTPs with diluted municipal wastewater from an environmental impact perspective. Consequently, more sustainable P recovery technologies with higher P recovery efficiency are needed. It is reasonable to expect that further incremental improvement of the current Airpex and Gifhorn based phosphorus recovery technologies cannot significantly increase environmental benefit from P recovery. Transformative technologies such as separation of black water from other domestic wastewater for P recovery (Verstraete & Vlaeminck., 2011) or more advanced membrane technology for direct phosphorus recovery from municipal wastewater (Qiu & Ting., 2014) might be able to achieve significantly higher environmental benefit. But it needs to point out that the benefit from P recovery should not be limited to positive environmental impact only because P recovery also alleviates the risk of phosphorus depletion within the next 50 to 100 years. This is why even with a small environmental benefit, many countries encourage P recovery in WWTPs. For example, Sweden has regulated that at least 60% P should be recovered from the total wastewater phosphorus (Hultman et al., 2004).

In terms of total environmental impacts in each category, **Figure S4** shows that the existing process had the lowest impact in HTP, AP, ADFP and FEP categories while the upgraded processes benefit EP and GWP categories. EP reduction in the upgraded processes was mainly due to nutrient removal, while GWP reduction was due to electricity recovery. The comparison between the three upgraded processes indicates that Process C had the lowest impact compared to Processes A and B in all categories (between 5 - 37%) due to less chemical consumption by AGS and a high nutrient removal efficiency. Thus, in terms of total environmental impact without considering economic cost, Process C that integrating nutrient removal by AGS, phosphorus recovery and electricity recovery is the best option for upgrading the Malaysian STP. This result could be the guideline to decision-makers for technology selection when considering technical and environmental impacts.

3.4 LCA of the existing process and the three upgraded processes with and without P recovery

P recovery from wastewater has been demonstrated at full scale, but it has not been widely adopted due to high cost. As a developing country, Malaysia is less likely to implement P recovery in the near future. It is thus very necessary to compare the environmental impacts of wastewater treatment processes with and without P recovery to provide quantitative data to allow operators, engineers or policymakers to make informed decisions when upgrading the existing wastewater treatment plants. Also, it can provide information to researchers to understand the environmental impact from phosphorus recovery. The comparative results of LCA between the existing process and the three upgraded processes (with and without P recovery) are shown in **Figure 4**. EP is mainly dependent on nitrogen and phosphorus concentrations in the effluent of WWTPs. It can be seen that EP was reduced by 62% in Process A, 67% in Process B and 76% in Process C, respectively, compared with that in the existing process, due to nutrient removal. GWP in upgraded processes was reduced to 7-22% compared to the existing process. It is due to the consequence of electricity generated in the upgraded processes. This reduction highlights the importance of electricity recovery to reduce global warming (Xu et al., 2014). HTP, AP, ADFP and FEP impacts from the upgraded processes were averagely 23% higher compared to the existing process due to increased chemical consumption, especially in Process B. In overall, the upgraded processes with nutrient removal and resource recovery in this study had positive environmental impacts on EP and GWP while there were negative impacts on HTP, AP, ADFP and FEP.

Figure 4 also shows the environmental impact comparison between two scenarios; i. the upgraded processes with nutrient removal only (without P recovery) and; ii. the upgraded processes with both nutrient removal and P recovery. Eutrophication impacts in Processes A, B and C were similar in both scenarios because EP was mainly affected by concentrations of pollutants in the effluent (i.e. TCOD, TN and TP). However, other impact categories such as HTP, AP, ADFP, GWP and FEP experienced negligible or small increase ranging from 0.9% to 7.6%, which are the net results from the additional energy and chemical demands for the phosphorus recovery. This indicates that P recovery in this study led to a negligible net impact on the environment. Instead, the substantial environmental loads imposed by the production of mineral fertiliser could be avoided indirectly (Hao et al., 2019).

3.5 Effects of the functional units on LCA results for the three upgraded processes with P recovery

The life cycle inventories of FU2 for all three processes are shown in **Table S5**. With per m^3 treated wastewater as FU1, Process B had the highest environmental burden due to its most chemical and energy consumption to treat per m^3 wastewater as shown in **Figure 5a**. However, by using per kg recovered struvite as FU2, the environmental impact from Process A was averagely 42% higher than those from Processes B and

C in all six categories as shown in **Figure 5b** due to high energy and chemical consumption for 1kg recovered struvite. It is mainly due to the low struvite recovery efficiency by Airprex in process A. The inconsistent results from two different functional units suggest the importance of FU selection in LCA, which should be based on different purposes. For the integrated wastewater treatment process with struvite recovery, FU2 is more suitable because it represents the environmental burden from per unit of P/struvite recovered. FU1 is more suitable for the comparison of processes or technologies for wastewater treatment only. Regardless of the functional unit, Process C always had the lowest impacts of six studied categories among all upgraded processes due to its cleanest effluent and lowest energy and chemical use. Therefore, Process C is recommended as the best technology with the least environmental burden from the aspects of wastewater treatment and struvite recovery. This further indicates the promising prospect of aerobic granular sludge technology for sustainable wastewater treatment.

3.6 Sensitivity analysis

The environmental impact results in this study show that Process C has the least environmental burdens. To further investigate how the variability of inventory data affects environmental impact results, we used Process C as a case study for a sensitivity analysis. **Table 3** shows the variability of environmental impact results by varying inventory data such as electricity consumption, nutrient concentrations in effluent and chemical consumption by ±10% in 20 years and ±20% of 40 years, respectively. All output variance is within the ranges of input variance. In general output variance corresponding to electricity is the highest while it is the least except eutrophication potential to nutrient concentrations in effluent. For example, environmental impact categories such as HTP, AP, ADFP, FEP and GWP varied from ±7.42% to ±9.98% to respond to the change in electricity consumption by ±10% (in 20 years) and these same impact categories varied from ±14.74% to ±19.92% from the change in electricity consumption by ±20% (in 40 years). EP changed by ±9.1% and ±18.05%, respectively, to respond to ±10% and ±20% changes in TP and TN concentrations in the effluent while the other five impact categories were almost unaffected. Finally, the variance of chemical consumption led to less effects on all outputs compared with electricity. The highest change corresponding to chemical input was FEP, which was ±6.62% in 20 years and ±13.04% in 40 years, respectively, much lower than the input variance. These results are in agreement with those reported by Piao et al. (2015) that variance in electricity consumption caused the most sensitive change to AP and HTP in all WWTPs studied. The fact that the variation in electricity consumption, chemical consumption and nutrient concentrations in the effluent by 10%-20% does not cause an environmental impact output change by more than 20% suggests a less sensitivity of environmental impact results to inventory data in this study. This means the results in this study from the current database are applicable for the WWTP with long design life or for the circumstance with a certain level of variability in the dataset.

3.7 Economic evaluation of the three upgraded processes

The life cycle costs (LCC) of the existing and the three upgraded processes with P recovery based on per population equivalent (PE) per day are shown in **Table 4**. Positive values represent the cost required for treatment/operation while negative values mean the money earned by the plant from the resource recovery. The total LCC of Process A, B and C are averagely 24% higher than that of the existing process (0.0092 USD/PE.day), with Process A having the lowest LCC in three upgraded processes. It is because that additional nutrient removal and resource recovery in upgraded processes increased capital cost and operating cost. Morelli et al. (2019) reported an increase in net life cycle cost of the upgraded process by 17% in a small community wastewater treatment plant with 3,800 m^3/day flowrates after being upgraded for biological nutrient removal with enhanced primary settling and anaerobic digestion (AD). This highlights roughly equivalent additional cost required for the upgrading of WWTPs in both large and small scale plants. Besides, the economic gains from the recovered electricity and phosphorus, and the reduced sludge disposal contributed to the reduction in the net life cycle cost in the three upgraded processes in this study. Similarly, Xu et al. (2014) reported that 13 sewage sludge treatments in China gained environmental and economic benefits by applying sludge digestion and electricity recovery. Although Process C had the lowest negative environmental impact, it had almost a similar life cycle cost with that of Process B. Processes B and C were 21.3% and 19.5% more expensive than Process A respectively, mainly due to the more chemical consumption in Gifhorn than Airprex process. Thus, from the point of view of economic cost, Process A (i.e. the integration of EBPR and nitrification-denitrification for nutrient removal, Airprex for P recovery and anaerobic digestion for electricity recovery with CHP) is the optimum option among the three upgrading processes.

4. Conclusions

Three processes were designed to upgrade a centralised wastewater treatment plant with SBR technology for nutrient removal and phosphorus recovery. All technologies selected for the upgrading are commercially available to ensure the practical feasibility of the upgraded wastewater treatment, and the meaningful results and conclusions to decision-makers and other researchers. To evaluate the environmental benefits/burdens of the existing and upgraded processes, environmental and economic assessments using LCA were carried out. The main conclusions are summarised as below.

- Upgrading the existing plant for nutrient removal, phosphorus recovery and electricity generation benefits the environment by reducing EP by 62-76%, and GWP by 7-22%. However, these environmental benefits were gained at the cost of increases in HTP, AP, ADFP and FEP by averagely 23%. Therefore, a trade-off between different environmental categories needs to be considered for upgrading especially when protecting the local water eco-system.
- The upgraded Process C is recommended as the best technology with the least environmental burden from the aspects of wastewater treatment and struvite recovery indicating promising prospects of aerobic granular sludge technology for upgrading the existing WWTPs with SBR technology for sustainable wastewater treatment due to its better nutrient removal performance and less chemical consumption.
- The added phosphorus recovery with either Airprex or Gifhorn technology only contributes to 2-5% environmental benefit. This is mainly due to the low influent phosphorus concentration in this study such as around 2.6 mg/L, leading to low P recovery efficiencies. The environmental benefit of phosphorus recovery could rise with an increase in influent phosphorus concentration. Therefore, it needs to be careful to consider adding phosphorus recovery units in WWTPs with diluted municipal wastewater from an environmental impact perspective.
- FU2 (per kg struvite recovered) is more suitable when considering the environmental impact from per kg P recovered from wastewater. FU1 (per m^3 wastewater) is more preferred to evaluate environmental performance for treating per m^3 wastewater. Process A with EBPR and Airprex has the highest environmental burden in terms of per kg P recovered while Process B with chemical P precipitation and Gifhorn shows the highest environmental impact in terms of per m^3 wastewater treated. Process C has the least environmental impact with either of FU. This provides a guideline for the process selection and highlights the environmental sustainability of aerobic granular sludge technology
- The total life cycle costs of Processes A, B and C were averagely 24% higher than the existing process (0.0092 USD/PE·day) due to increased capital and operating costs. Process C was 19.5% more expensive than Process A mainly due to the more chemical consumption in Gifhorn than Airprex process although Process C had the lowest environmental impact. When phosphorus recovery is needed, more technology combinations such as coupling aerobic granular sludge for nutrient removal with Airprex for phosphorus recovery need to be explored to achieve both minimum environmental impact and economic cost.

This work identified the importance of considering both local wastewater characteristics and the current technology being used in the existing process for selecting technology and relevant process configurations to upgrade an existing WWTP. In addition, technological, economic and environmental assessment is critical to compare different processes to get the best option. The quantitative information from this study could guide decision-making to upgrade existing WWTPs especially in regions with diluted wastewater, which can underpin the transition towards sustainable wastewater treatment.

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Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery：environmental and economic life cycle performance

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Figures

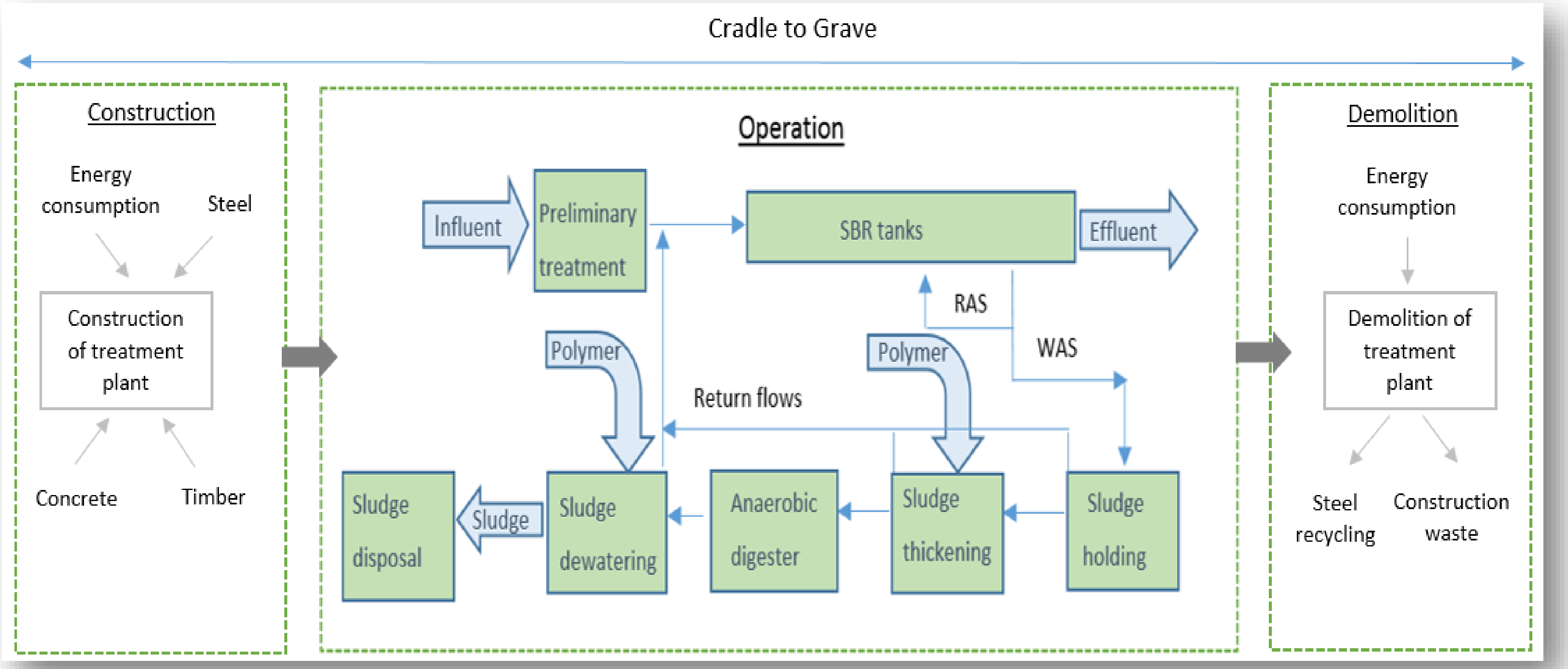

Figure 1. Schematic diagram of the existing Malaysian STP in the system boundary of this study with 40-year operation. Note: SBR = sequencing batch reactor, RAS = return activated sludge, WAS = waste activated sludge

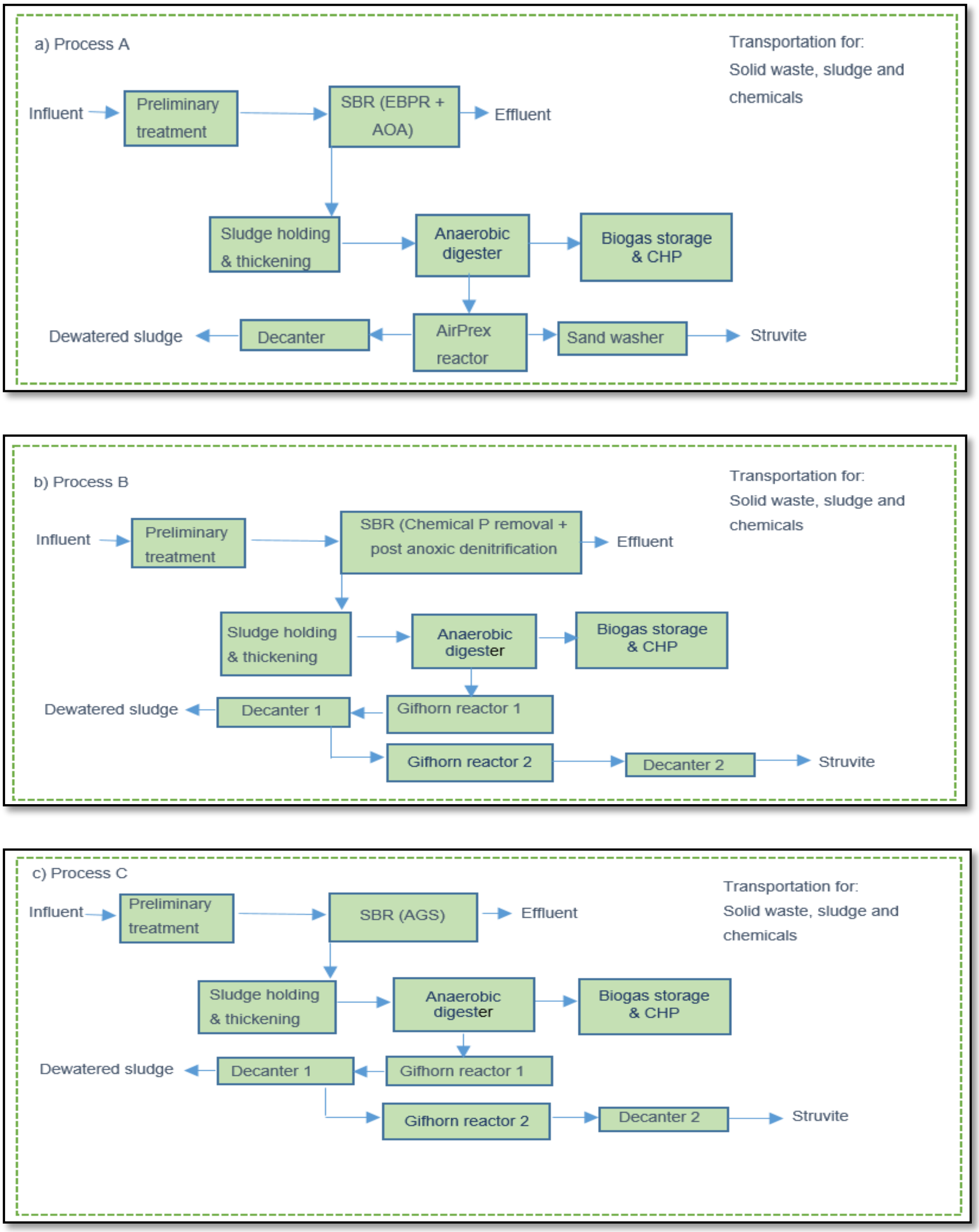

Figure 2. Schematic diagrams of the three upgraded Processes A, B and C which include the existing operating units and additional units after upgrading for nutrient removal in SBR and phosphorus recovery. Note: (SBR = sequencing batch reactor; EBPR= enhanced biological phosphorus removal, AOA = anaerobic, aerobic anoxic, AGS = aerobic granular sludge, AD = anaerobic digestion)

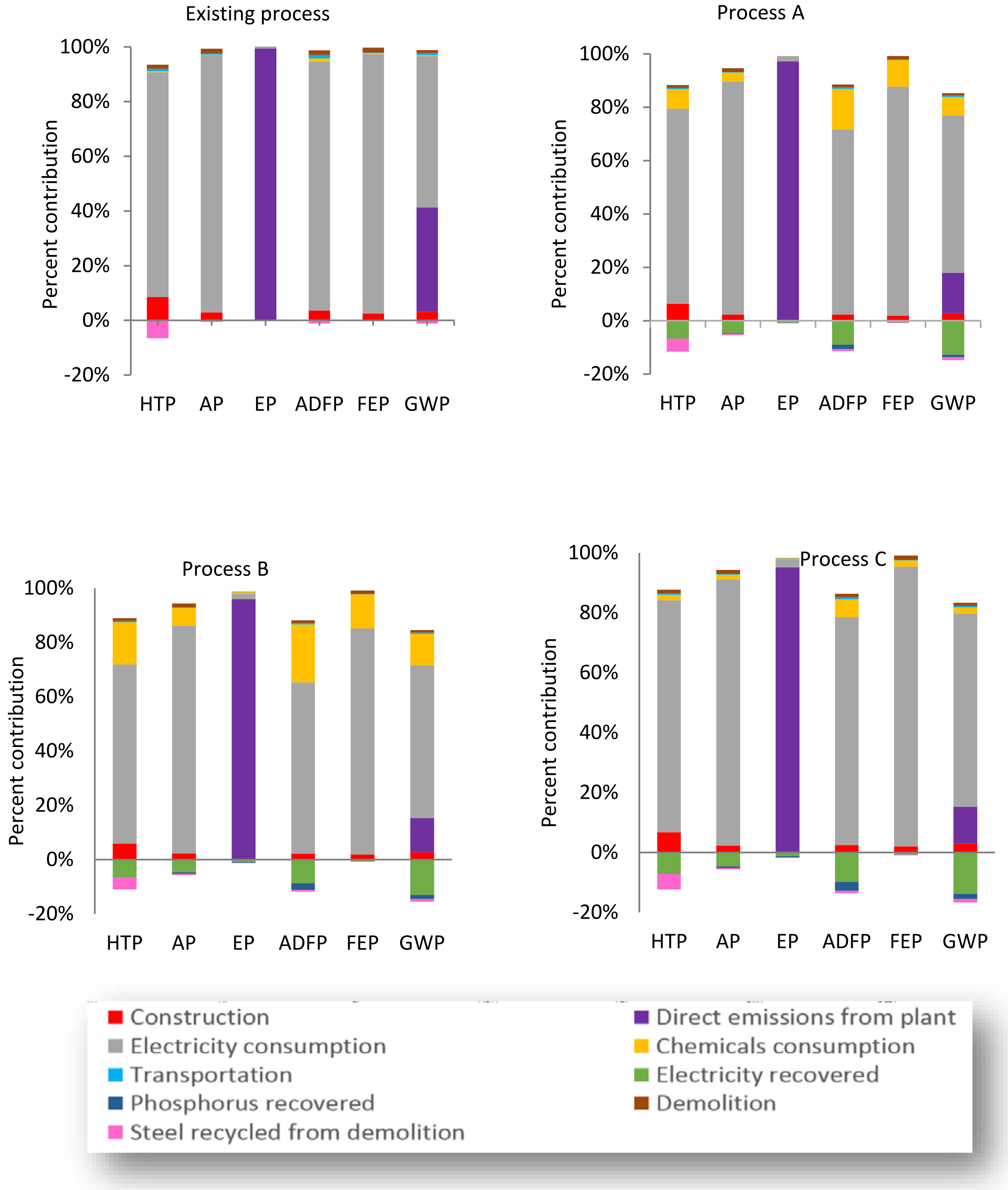

Figure 3. Environmental impact contribution analysis based on different factors in the existing process and the three upgraded processes by using FU1. Note: (HTP-human toxicity potential, AP-acidification potential, EP-eutrophication potential, ADFP-abiotic depletion (fossil fuel) potential, FEP-freshwater ecotoxicity potential, and GWP-global warming potential).

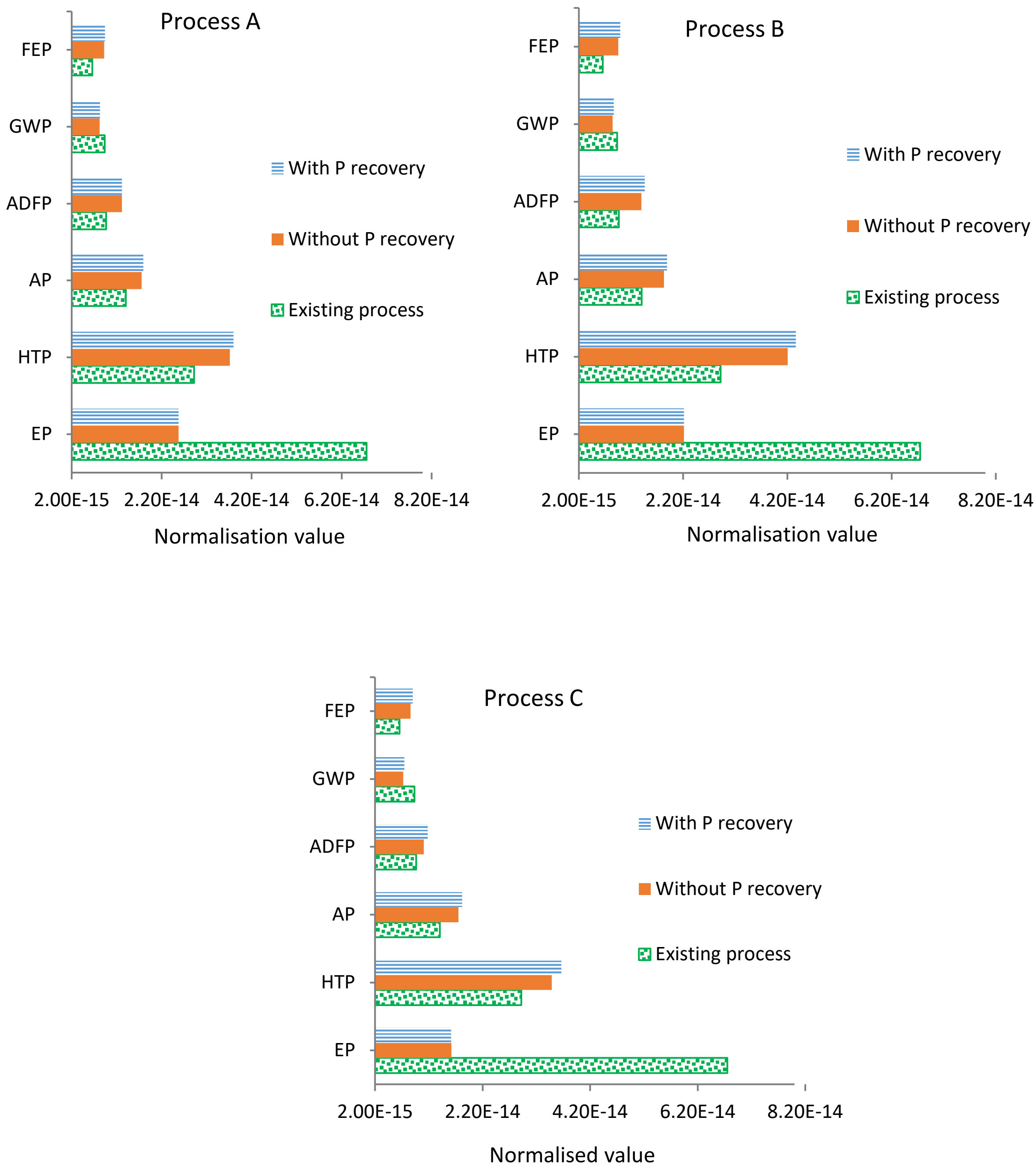

Figure 4. Comparison of environmental impacts between the existing process and the three upgraded processes with nutrient removal only (without P recovery), and the upgraded processes with both nutrient removal and P recovery by using FU1

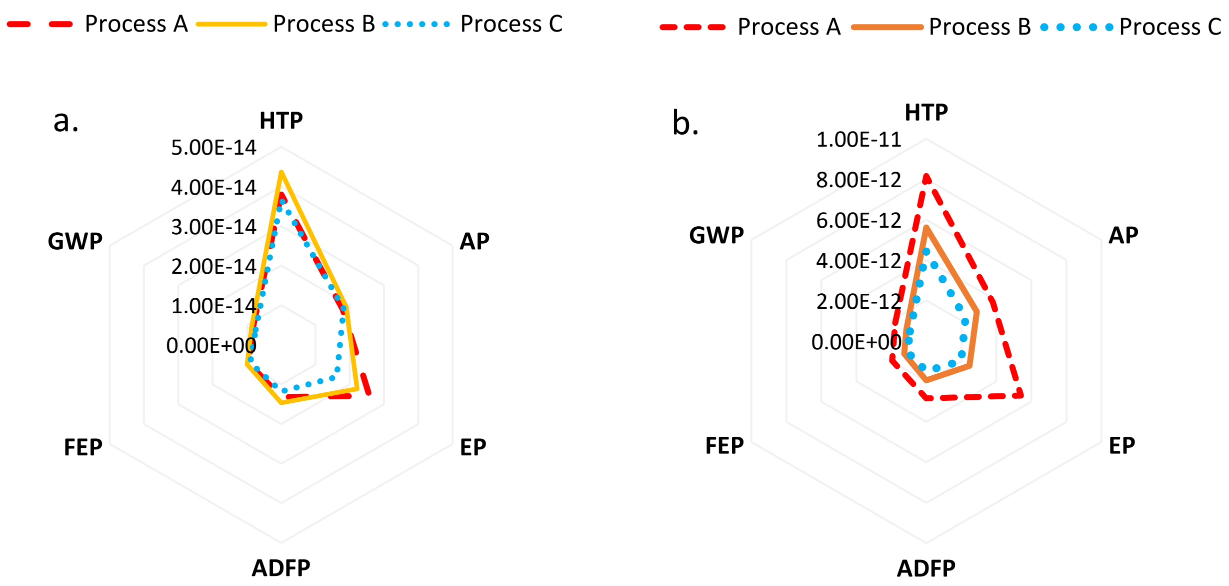

Figure 5. Comparison of environmental impacts from the three upgraded processes by using FU1 (1 m^3 treated wastewater) and FU2 (1 kg struvite recovered)

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Tables

Table 1. Comparison of nutrient removal and phosphorus recovery performance between the existing process and the three upgraded processes

Parameters	Unit	Existing process	Process A	Process B	Process C
Total suspended solids removal rate	%	92	92	92	92
Total biochemical oxygen demand removal rate	%	90	90	90	90
Total nitrogen removal rate	%	46	83	86	90
Total phosphorus removal rate	%	60	92	93	98
Dry weight of dewatered sludge cake	kg/day	25,500	18,900	19,900	19,000
Struvite recovered	kg/day	-	712	1,147	1,216
Phosphorus recovered	kg/day	-	90	145	154

Table 2. Comparison of energy consumption and generation in the existing process and the three upgraded processes

Parameters	Unit	Existing process	Process A	Process B	Process C
Methane gas production	m^3/day	-	2,580	2,773	2,665
Total electricity generated from CHP	kWh/day	-	10,426	11,380	10,784
Total electricity consumption for P recovery	kWh/day	-	928	1,001	1,061
Total electricity consumption for secondary treatment (SBR)	kWh/day	18,121.2	26,044	26,787	27,471
Total electricity consumption per day	kWh/day	30,609	40,084	40,900	41,644
Net electricity consumption per day (total electricity consumption – total electricity generated)	kWh/day	30,609	29,658	29,520	30,860

Table 3. Sensitivity analysis result by changing selected inventory data by ±10% and ±20% for Process C in 20 years and 40 years, respectively, according to 1m^3 of treated wastewater (FU1)

	Process C in 20 years (±10%)			Process C in 40 years (±20%)		
Inventory components:-	Electricity consumption	TN&TP in effluent	Chemical consumption	Electricity consumption	TN&TP in effluent	Chemical consumption
Life cycle impacts:						
Human toxicity (HTP)	±9.90	±0.00	±2.90	±19.60	±0.00	±5.72
Acidification (AP)	±9.98	±0.00	±0.65	±19.92	±0.00	±1.29
Eutrophication (EP)	±0.55	±9.10	±0.07	±1.11	±18.05	±0.13
Abiotic depletion (fossil fuels)(ADFP)	±9.83	±0.00	±1.94	±19.53	±0.00	±3.77
Fresh water aquatic ecotox.(FEP)	±9.96	±0.00	±6.62	±19.91	±0.00	±13.04
Global warming (GWP)	±7.42	±0.00	±2.35	±14.74	±0.00	±4.66

TN and TP = Total nitrogen and total phosphorus

Table 4. Life cycle costs of the existing and the three upgraded processes in construction and operation phases

Phase	Construction	Operation				Benefit from operation		
Cost (USD/ PE.day)	Capital cost	Electricity consumption	Chemicals consumption	Transport	Disposal fee in landfill	Electricity recovered	Phosphorus recovered	Life cycle cost
Existing process	1.7E-3	6.5E-3	3.9E-4	3.7E-4	2.0E-4	-	-	9.20E-3
Process A	2.5E-3	8.4E-3	1.2E-3	2.7E-4	1.5E-4	-2.1E-3	-1.7E-4	1.03E-2
Process B	4.6E-3	8.6E-3	2.0E-3	2.9E-4	1.5E-4	-2.3E-3	-2.7E-4	1.31E-2
Process C	4.5E-3	8.8E-3	1.6E-3	2.7E-4	1.5E-4	-2.2E-3	-2.9E-4	1.28E-2

Supplementary information

Upgrading a large and centralised municipal wastewater treatment plant with sequencing batch reactor technology for integrated nutrient removal and phosphorus recovery: environmental and economic life cycle performance

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Tables

Table S1. Water quality parameters of the existing process of Malaysian STP

Parameters	Unit	Influent	Inlet to aeration tank	Effluent	Inlet to sludge treatment
Population equivalent	PE	662,002.0			
Total suspended solids (TSS)	mg/L	174.0 ±10.5	150.0 ±10.4	14.6 ±5.8	5980.0 ±330.0
Total biochemical oxygen demand ($TBOD_5$)	mg/L	126.0 ±11.0	66.4 ±10.5	10.1 ±1.6	765.0 ±21.2
Total chemical oxygen demand (TCOD)	mg/L	433.0 ±21.3	304.0 ±19.5	44.7 ±3.1	5109.0 ±250.5
Total nitrogen (TN)	mg/L	28.0 ±2.2	27.0 ±2.1	15.0 ±1.5	210.0 ±11.3
Total phosphorus (TP)	mg/L	2.6 ±0.07	2.5 ±0.04	1.1 ±0.03	18.0 ±1.60
COD:N:P ratio	-	167:11:1	122:11:1	41:14:1	284:12:1

Table S2. Chemical consumption in each upgraded process for nutrient removal and phosphorus recovery

Chemicals consumption	Unit	Process A	Process B	Process C
For nitrogen removal:				
Methanol (CH_3OH)	kg/day	3570.4	3904.2	-
For phosphorus removal:				
Iron chloride III ($FeCL_3$)	kg/day	-	2279.7	-
For phosphorus recovery:				
Magnesium chloride ($MgCl_2$)	kg/day	1306.2	-	-
98% Sulfuric acid (H_2SO_4)	kg/day	-	1189.6	1261.1
Sodium sulfide (Na_2S)	kg/day	-	116.1	123.0
Sodium hydroxide ($Na(OH)_2$)	kg/day	-	420.7	446.0
Magnesium hydroxide ($Mg(OH)_2$)	kg/day	-	29.0	30.8

Table S3. Design parameters of the existing process and three upgraded processes

Parameters	Unit	Existing process	Process A	Process B	Process C
Cycle time in SBR	hour	4.0	6.0	6.0	5.0
Total treating capacity	m^3/d	148,950.0	148,950.0	148,950.0	148,950.0
pH range	-	6.8-8.0	7.0-7.5	7.0-8.0	6.5-8.0
Operating temperature	^oC	20.0	20.0	20.0	20.0
Total air supply rate in SBR	m^3/d	259,200.0	475,414.7	496,103.3	515,152.1
Oxygen required for additional nitrification	kg/day	-	8,125.6	8,885.5	9,585.1
Total electricity consumption from blowers	kWh/day	8,520.0	17,067.0	17,809.8	18,493.7
Electricity demand of P recovery process	kWh/day	-	927.8	1,001.0	1,061.2
Total electricity consumption per day	kWh/day	30,609.2	40,084.0	40,900.2	41,644.4

Table S4. Life cycle inventories of the existing and three upgraded processes. Values are presented based on per m^3 of treated wastewater as functional unit 1 (FU 1)

Parameters	Unit	Existing	Process A[a]	Process B[b]	Process C[c]
Transport for:					
1.Solid waste disposal	t.km/m^3	1.81E-05	1.81E-05	1.81E-05	1.81E-05
2.Sludge disposal	t.km/m^3	6.46E-03	4.78E-03	5.04E-03	4.81E-03
3.Chemicals	t.km/m^3	2.58E-05	5.15E-05	7.73E-05	6.44E-05
Sub-total	t.km/m^3	*6.50E-03*	*4.85E-03*	*5.13E-03*	*4.89E-03*
Chemicals consumption:					
4.Polyelectrolyte	kg/m^3	5.15E-04	5.15E-04	5.15E-04	5.15E-04
For nutrients removal;					
5.Methanol (CH_3OH)	kg/m^3	-	2.40E-02	2.62E-02	-
6.Iron chloride III ($FeCL_3$)	kg/m^3	-	-	1.53E-02	-
For phosphorus recovery;					
7.Magnesium chloride ($MgCl_2$)	kg/m^3	-	8.77E-03	-	-
8.98% Sulfuric acid (H_2SO_4)	kg/m^3	-	-	7.99E-03	8.47E-03
9.Sodium sulfide (Na_2S)	kg/m^3	-	-	7.79E-04	8.26E-04
10.Sodium hydroxide $Na(OH)_2$	kg/m^3	-	-	2.82E-03	2.99E-03
11.Magnesium hydroxide $Mg(OH)_2$	kg/m^3	-	-	1.95E-04	2.07E-04
Electricity input:					
12.Electricity consumption	kWh/m^3	2.05E-01	2.69E-01	2.75E-01	2.80E-01
Avoided products:					
13.Electricity generated	kWh/m^3	0.00E+00	7.00E-02	7.64E-02	7.24E-02
14.Struvite ($MgNH_4PO_4$)	kg/m^3	-	4.78E-03	7.70E-03	8.16E-03
15.Phosphate fertilizer	kg/m^3	-	6.05E-04	9.74E-04	1.03E-03
Emission to air:					
16.Carbon dioxide (CO_2)-biogenic	kg/m^3	8.93E-02	8.55E-02	8.50E-02	8.62E-02
17.Methane (CH_4)	kg/m^3	1.10E-03	6.82E-04	6.93E-04	7.04E-04
18.Dinitrogen monoxide (N_2O)	kg/m^3	4.60E-04	5.70E-04	5.75E-04	5.80E-04
Effluent to rivers:					
19.Chemical oxygen demand (COD)	kg/m^3	4.47E-02	4.47E-02	4.47E-02	4.47E-02
20.Total nitrogen (TN)	kg/m^3	1.50E-02	5.40E-03	4.40E-03	3.15E-03
21.Total phosphorus (TP)	kg/m^3	1.05E-03	2.40E-04	1.90E-04	6.00E-05
Materials for construction:					
22.Steel	kg/ m^3	2.13E-03	2.35E-03	2.45E-03	2.45E-03
23.Concrete	m^3/ m^3	1.79E-05	1.97E-05	2.06E-05	2.06E-05
24.Timber	kg/ m^3	1.20E-06	1.32E-06	1.38E-06	1.38E-06
25.Energy consumption	kWh/ m^3	4.69E-03	5.16E-03	5.39E-03	5.39E-03
Demolition:					
26.Energy consumption	kWh/ m^3	3.79E-03	4.17E-03	4.36E-03	4.36E-03
27.Construction waste	kg/ m^3	3.45E-02	3.79E-02	3.96E-02	3.96E-02
28.Steel recycling	kg/ m^3	2.18E-03	2.40E-03	2.50E-03	2.50E-03

[a] Nutrient removal by nitrification and denitrification (AOA) and EBPR, and P recovery by Airprex technology;
[b] Nutrient removal by nitrification, post anoxic denitrification, and ferric precipitation and P recovery by Gifhorn technology;
[c] Nutrient removal by AGS, and P recovery by Gifhorn technology;
(EBPR= enhanced biological phosphorus removal; AOA = anaerobic:aerobic:anoxic; AGS = aerobic granular sludge)

Table S5. Life cycle inventories of the three upgraded processes. Values are presented based on per kg of struvite recovered from wastewater as functional unit 2 (FU2)

Parameters	Unit	Process A	Process B	Process C
Transport for:				
1.Solid waste	t.km/kg struvite	3.79E-03	2.35E-03	2.22E-03
2.Sludge	t.km/kg struvite	1.00E+00	6.54E-01	5.89E-01
3.Chemicals	t.km/kg struvite	1.08E-02	1.00E-02	7.89E-03
Sub-total	t.km/kg struvite	**1.01E+00**	**6.67E-01**	**6.00E-01**
Chemicals consumption:				
4.Polyelectrolyte	kg/kg struvite	1.08E-01	6.69E-02	6.31E-02
For nutrients removal;				
5.Methanol (CH_3OH)	kg/kg struvite	5.01E+00	3.41E+00	-
6.Iron chloride III ($FeCL_3$)	kg/kg struvite	-	1.99E+00	-
For phosphorus recovery:				
7.Magnesium chloride ($MgCl_2$)	kg/kg struvite	1.83E+00	-	-
8.98% Sulfuric acid (H_2SO_4)	kg/kg struvite	-	1.04E+00	1.04E+00
9. Sodium sulfide (Na_2S)	kg/kg struvite	-	1.01E-01	1.01E-01
10. Sodium hydroxide ($Na(OH)_2$)	kg/kg struvite	-	3.67E-01	3.67E-01
11. Magnesium hydroxide ($Mg(OH)_2$)	kg/kg struvite	-	2.53E-02	2.53E-02
Electricity input:				
12.Electricity consumption	kWh/kg struvite	5.63E+01	3.57E+01	3.43E+01
Avoided products:				
13.Electricity generated	kWh/kg struvite	1.46E+01	9.93E+00	8.87E+00
14.Struvite ($MgNH_4PO_4$)	kg/kg struvite	1.00E+00	1.00E+00	1.00E+00
15.Phosphate fertilizer	kg/kg struvite	1.27E-01	1.27E-01	1.27E-01
Emission to air:				
16.Carbon dioxide (CO_2)-biogenic)	kg/kg struvite	1.24E-01	1.20E-01	1.35E-01
17.Methane (CH_4)	kg/kg struvite	2.30E-01	1.43E-01	1.35E-01
18.Dinitrogen monoxide (N_2O)	kg/kg struvite	3.46E-02	1.73E-02	1.24E-02
Effluent to river:				
19.Chemical oxygen demand (COD)	kg/kg struvite	9.35E+00	5.81E+00	5.48E+00
20.Total nitrogen (TN)	kg/kg struvite	1.13E+00	5.72E-01	3.86E-01
21.Total phosphorus (TP)	kg/kg struvite	5.02E-02	2.47E-02	7.35E-03
Materials for construction:				
22.Steel	kg/kg struvite	4.91E-01	3.19E-01	3.00E-01
23.Concrete	m^3/kg struvite	4.13E-03	2.68E-03	2.53E-03
24.Timber	kg/kg struvite	2.75E-04	1.79E-04	1.69E-04
25.Energy consumption	kWh/kg struvite	1.08E+00	7.01E-01	6.61E-01
Demolition:				
26.Energy consumption	kWh/kg struvite	8.72E-01	5.66E-01	5.34E-01
27.Construction waste	kg/kg struvite	7.93E+00	5.15E+00	4.86E+00
28.Steel recycling	kg/kg struvite	5.01E-01	3.25E-01	3.07E-01

[a] Nutrient removal by EBPR & nitrification and denitrification (AOA), and P recovery by Airprex technology;
[b] Nutrient removal by ferric precipitation & post anoxic denitrification, and P recovery by Gifhorn technology;
[c] Nutrient removal by AGS, and P recovery by Gifhorn technology;
(EBPR= enhanced biological phosphorus removal; AOA = anaerobic:aerobic:anoxic; AGS = aerobic granular sludge)

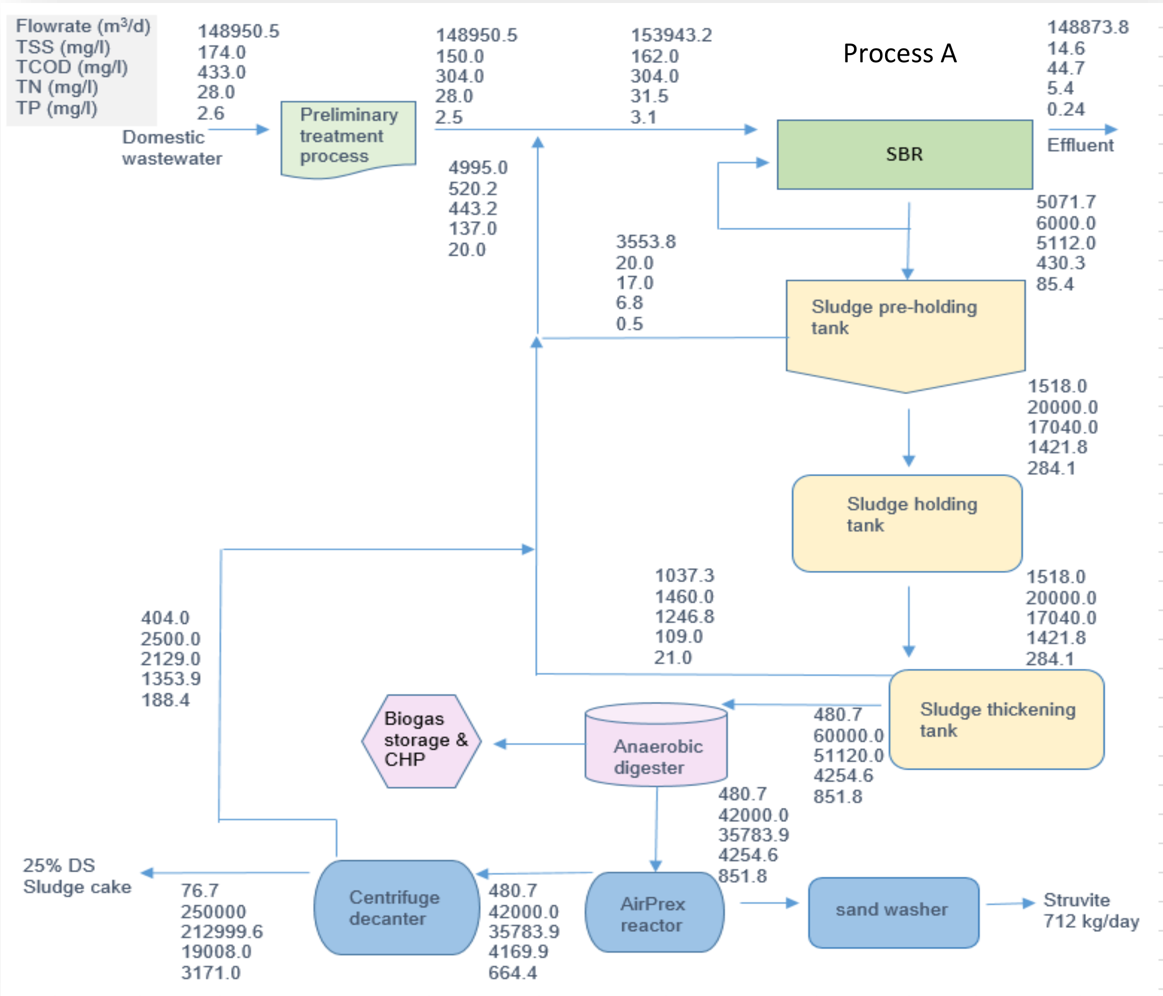
Table S6. Equations used for mass balance calculation of solid and nutrients in the upgraded processes

A	Solids mass balance	Description
1)	Sludge production from SBR	
i	$Qs,i = Qp,e + Qr,t$	Qs,i is total SBR influent flow rate
		Qp,e is preliminary treatment effluent flow rate
		Qr,t is total flow rate of recycle streams returning to inlet of SBR
ii	$TSSs,i = TSSp,e + TSSr,t$	TSSs,i is TSS load in SBR influent
		TSSp,e, is TSS load in preliminary treatment effluent
		TSSr,t is TSS load in recycle streams
iii	$\gamma_0 = MLSS_0 / CODremoval$	γ_0 = biomass yield in the existing process of Malaysian STP
		$MLSS_0$ is excess biosolids produced from SBR before upgrade
		CODremoval is daily mass of COD removed from SBR
iv	$MLSSe = \gamma \times CODremoval$	MLSSe is excess sludge production from SBR after upgrade
		γ is sludge yield in different processes
		CODremoval is load of COD removed through assimilation in SBRs
v	$TSSp = TSSremoval + MLSSe$	$TSSp$ is total sludge production
		TSSremoval is load of TSS removed from SBR
		MLSSe is excess sludge production from SBR after upgrade
vi	$COD_t = a'' \times TSSp \times (MLVSS/ MLSS)$	CODt is load of COD incorporated in wasted sludge
		a’’ is oxygen requirement to oxidize 1kg of COD which is represented as $C_5H_7O_2N$
		TSSp is total sludge production
		MLVSS/MLSS ratio in 3 upgraded processes was 60% due to lack of facility to separate sludge ash from wasted sludge
2)	Performance of solids processing facilities and impact of return flows	
i	Solid captures of gravity belt thickener and centrifuge decanter	
	$SSinlet \times Qinlet = SSoutlet \times Qoutlet + SSreturn \times Qreturn$	SSinlet is sludge solids concentration in solids processing facility influent
		SSoutlet is solids concentration in processed sludge
		SSreturn is solids concentration in corresponding recycle stream
		Qinlet is flow rate of facility influent
		Qoutlet is flow rate of processed sludge

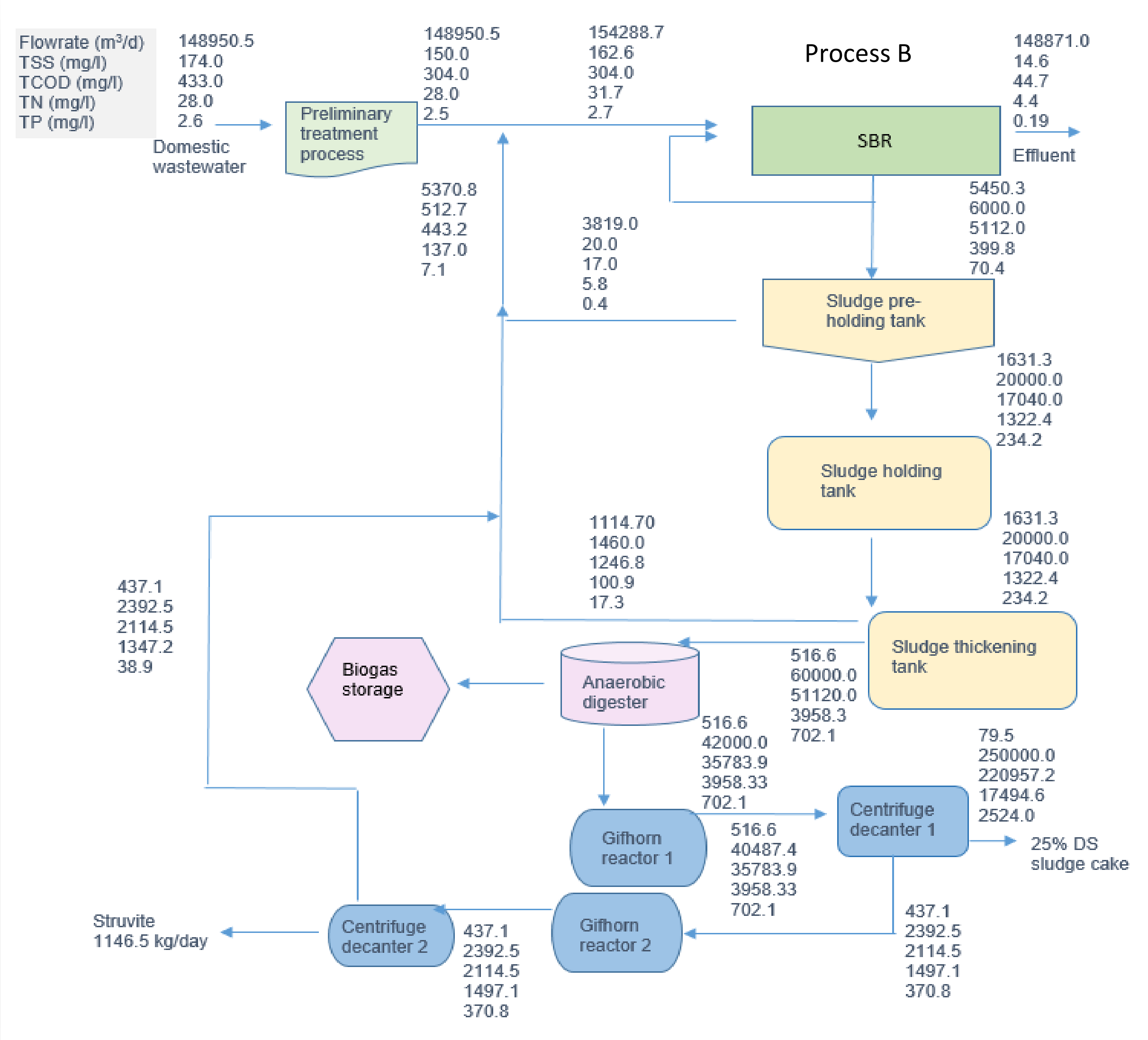
		Qreturn is flow rate of corresponding recycle stream
ii	$Qoutlet$ = ($SSinlet \times Qinlet \times R$)/ $SSoutlet$	Qoutlet is flow rate of thickened sludge and dewatered sludge from gravity belt thickener and centrifuge decanter
		Qinlet is flow rate of facility influent
		R is solid capture of different facilities
		SSinlet is sludge solids concentration in solids processing facility influent
		SSoutlet is solids concentration in processed sludge
iii	$CODt,outlet = a'' \times SSoutlet \times Qoutlet \times (MLVSS\ /MLSS)$	CODt,outlet is total COD load in wasted sludge
		a'' is oxygen requirement to oxidize 1kg of COD which is represented as $C_5H_7O_2N$
		SSoutlet is solids concentration in processed sludge
		Qoutlet is flow rate of processed sludge
		MLVSS/MLSS ratio in 3 upgraded processes was 60% due to lack of facility to separate sludge ash from wasted sludge
iv	$SSreturn = (SSinlet \times Qinlet \times (100\% - R))\ /Qreturn$	SSreturn is suspended solid concentrations in recycle streams
		SSinlet is sludge solids concentration in solids processing facility influent
		Qinlet is flow rate of facility influent
		Qreturn is flow rate of corresponding recycle stream
		R is solid capture of different facilities
v	$CODt,return = CODt,inlet - CODt,outlet$	CODt,return = total COD load in return flows/ corresponding recycle stream
		CODt,inlet is total COD mass load in facility influent
		CODt,outlet is total COD load in processed sludge
vi	$CODconsumed = a'' \times 18 \times Qinlet \times (MLVSS/\ MLSS)$	CODconsumed is daily mass of COD consumed for biogas production
		a'' is oxygen requirement to oxidize 1kg of COD
		Qinlet is flow rate of facility influent
		MLVSS/MLSS ratio in 3 upgraded processes was 60%
vii	$Qeffluent = Qinfluent - Qdecanter,outlet$	Qeffluent is Malaysian STP effluent flow rate after upgrade
		Qinfluent is flow rate of facility influent
		Qdecanter,outlet is flow rate of dewatered sludge from centrifuge decanter
B.	**Nutrient Mass Balance**	
1)	Nutrient removal from SBR	

i	$TP/TNremoval = TP/TNs,i \times RP/RN$	TP/TNremoval is daily mass of P and N removed in SBRs
		TP/TN$s,i$ is mass load of TP and TN in SBR influent
		RP/RN is total phosphorus removal rate in SBR
ii	$TP/TNeffluent = TP/TNs,i \times (100\% - RP/RN)$	TP/TNeffluent is TP and TN load in Malaysian STP effluent after upgrade
iii	$Ppoly = TPremoval - Passimilated$	Ppoly is daily mass of poly-P produced from SBR in Process A
		P/Nassimilated is phosphorus and nitrogen assimilated in SBR
iv	$Pprecipitation = TPremoval - Passimilated$	Pprecipitation is phosphate precipitation in Process B and Process C
v	$Nnitrified = TNremoval - Nassimilated$	Nnitrified and Ndenitrified is nitrogen removed by alternating nitrification and denitrification from all 3 upgraded processes
vi	$Ndenitrified = 0.98 \times Nnitrified$	
vii	$Ncell = 0.0196 \times Nnitrified + Nassimilated$	Ncell is daily mass of TN incorporated into cells and flowed into sludge treatment process
2)	Nutrient content in processed sludge and recycle streams	
i	$TNoutlet = Nsoluble,outlet + Ncell,inlet \times R$	TNoutlet is daily mass of TN in processed sludge in all 3 upgraded processes
		Nsoluble,outlet is daily mass of soluble N
		Ncell,inlet is cell-N load in facility influent
		R is solid capture of different facilities
ii	$TPreturn = TPsoluble,return + Ppoly,inlet \times (100\% - R) + Pcell,inlet \times (100\% - R)$	TPreturn is TP in recycle streams from clarifier, gravity belt thickener and centrifuge decanter
		Ppoly,inlet is poly-P load in facility influent
		Pcell,inlet is cell-P load in facility influent
iii	$TNreturn = TNsoluble,return + Ncell,inlet \times (100\% - R)$	TNreturn is TN in recycle streams

Figures



Flowrate (m³/d)
TSS (mg/l)
TCOD (mg/l)
TN (mg/l)
TP (mg/l)
148950.5
174.0
433.0
28.0
2.6
Domestic wastewater
Preliminary treatment process
148950.5
150.0
304.0
28.0
2.5
153943.2
162.0
304.0
31.5
3.1
Process A
148873.8
14.6
44.7
5.4
0.24
Effluent
SBR
4995.0
520.2
443.2
137.0
20.0
5071.7
6000.0
5112.0
430.3
85.4
3553.8
20.0
17.0
6.8
0.5
Sludge pre-holding tank
1518.0
20000.0
17040.0
1421.8
284.1
Sludge holding tank
1037.3
1460.0
1246.8
109.0
21.0
1518.0
20000.0
17040.0
1421.8
284.1
404.0
2500.0
2129.0
1353.9
188.4
Biogas storage & CHP
Anaerobic digester
480.7
60000.0
51120.0
4254.6
851.8
Sludge thickening tank
480.7
42000.0
35783.9
4254.6
851.8
25% DS Sludge cake
76.7
250000
212999.6
19008.0
3171.0
Centrifuge decanter
480.7
42000.0
35783.9
4169.9
664.4
AirPrex reactor
sand washer
Struvite 712 kg/day


Flowrate (m³/d)
TSS (mg/l)
TCOD (mg/l)
TN (mg/l)
TP (mg/l)
148950.5
174.0
433.0
28.0
2.6
Domestic wastewater
Preliminary treatment process
148950.5
150.0
304.0
28.0
2.5
154288.7
162.6
304.0
31.7
2.7
Process B
SBR
148871.0
14.6
44.7
4.4
0.19
Effluent
5370.8
512.7
443.2
137.0
7.1
3819.0
20.0
17.0
5.8
0.4
5450.3
6000.0
5112.0
399.8
70.4
Sludge pre-holding tank
1631.3
20000.0
17040.0
1322.4
234.2
Sludge holding tank
1631.3
20000.0
17040.0
1322.4
234.2
1114.70
1460.0
1246.8
100.9
17.3
437.1
2392.5
2114.5
1347.2
38.9
Sludge thickening tank
Biogas storage
Anaerobic digester
516.6
60000.0
51120.0
3958.3
702.1
516.6
42000.0
35783.9
3958.33
702.1
79.5
250000.0
220957.2
17494.6
2524.0
Gifhorn reactor 1
Centrifuge decanter 1
516.6
40487.4
35783.9
3958.33
702.1
25% DS sludge cake
Struvite
1146.5 kg/day
Centrifuge decanter 2
437.1
2392.5
2114.5
1497.1
370.8
Gifhorn reactor 2
437.1
2392.5
2114.5
1497.1
370.8

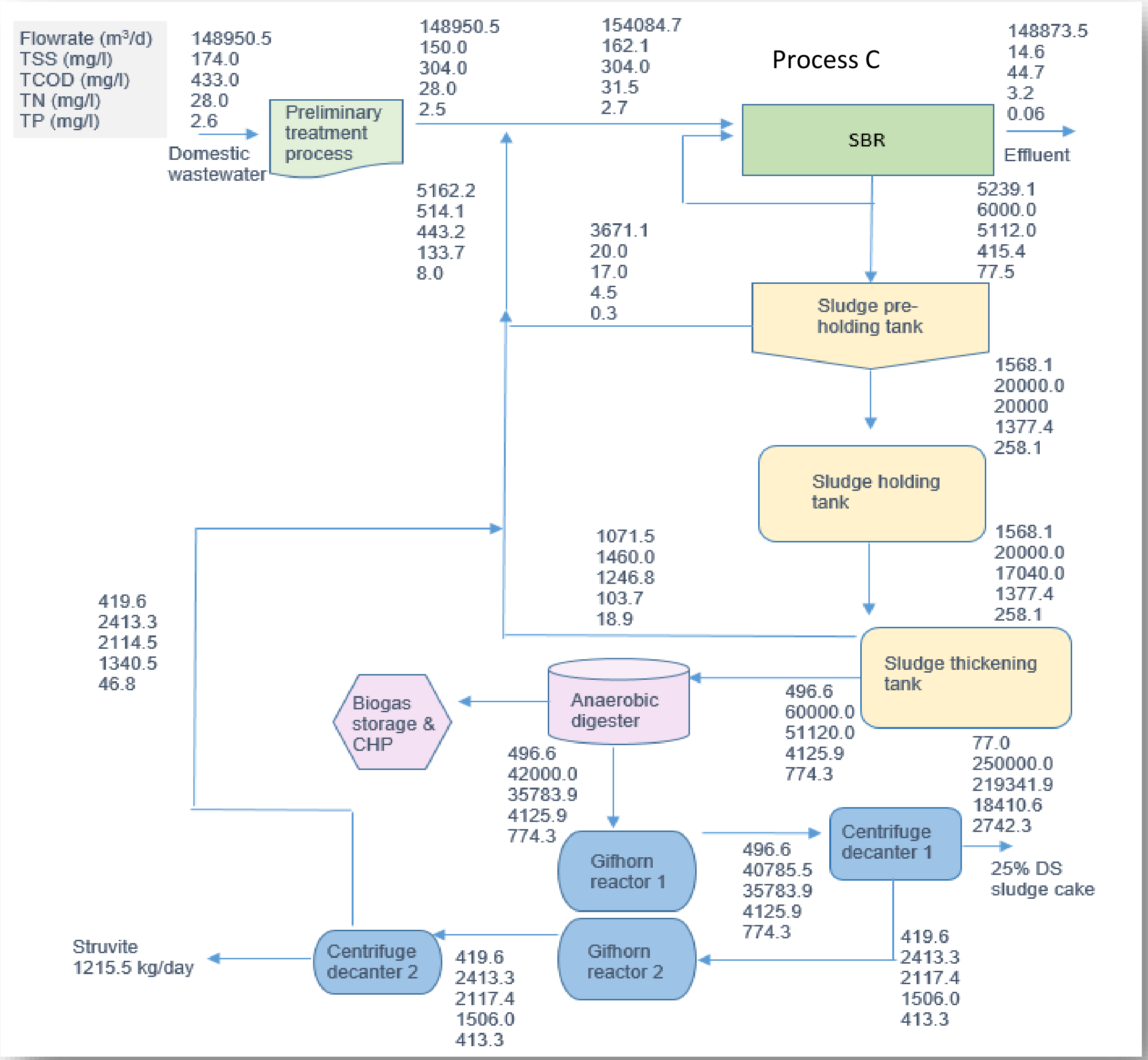


Figure S1. Mass balance for the three upgraded processes. Note: Process A is based on enhanced biological phosphorus removal (EBPR) for phosphorus (P) removal, nitrification and denitrification for nitrogen removal and AirPrex for P recovery. Process B uses ferric precipitation to remove phosphorus, nitrification and denitrification to remove nitrogen, and Gifhorn to recover P from sludge. Process C adopts aerobic granular sludge (AGS) technology for simultaneous biological nitrogen and phosphorus removal, and Gifhorn for P recovery.

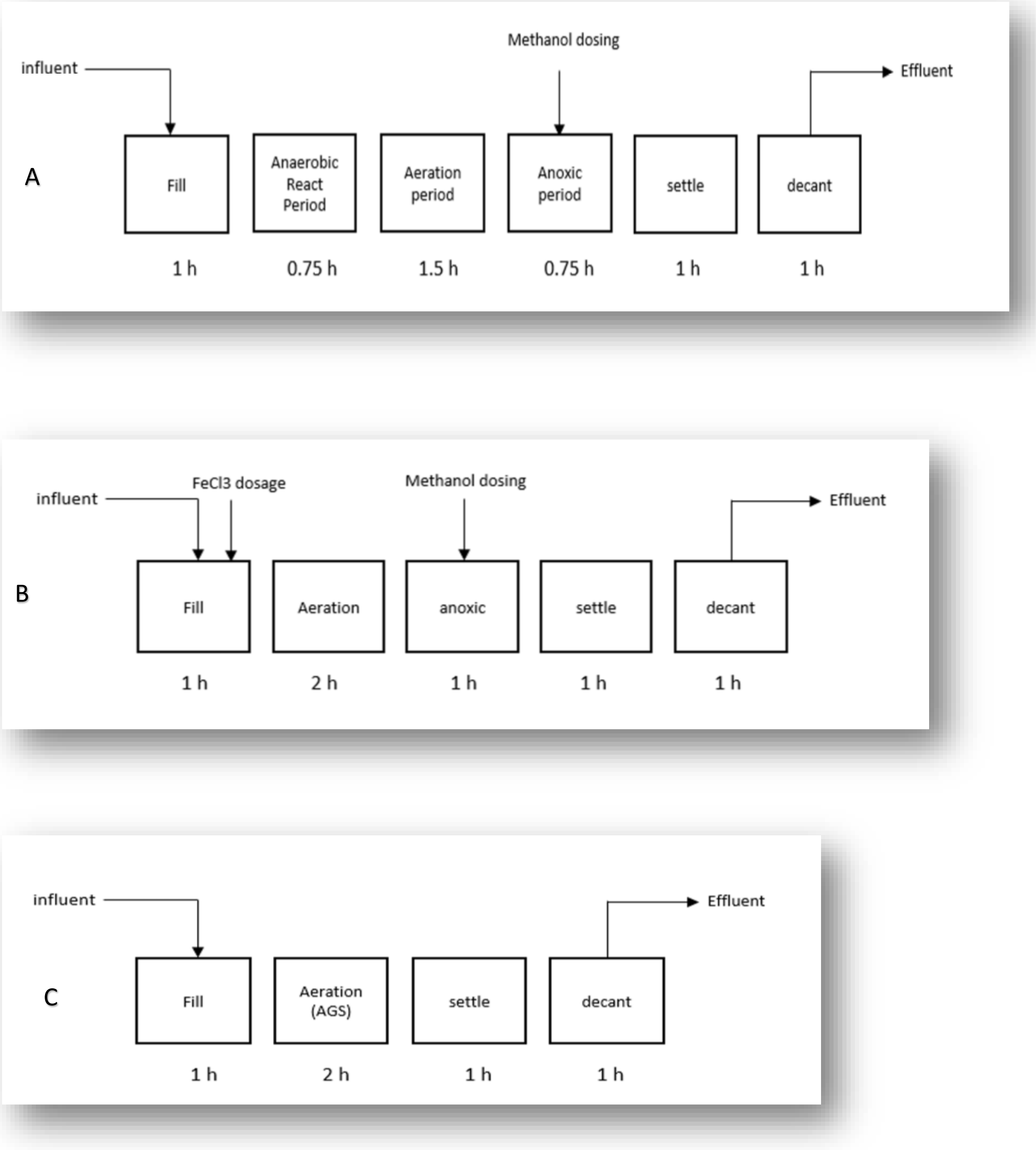
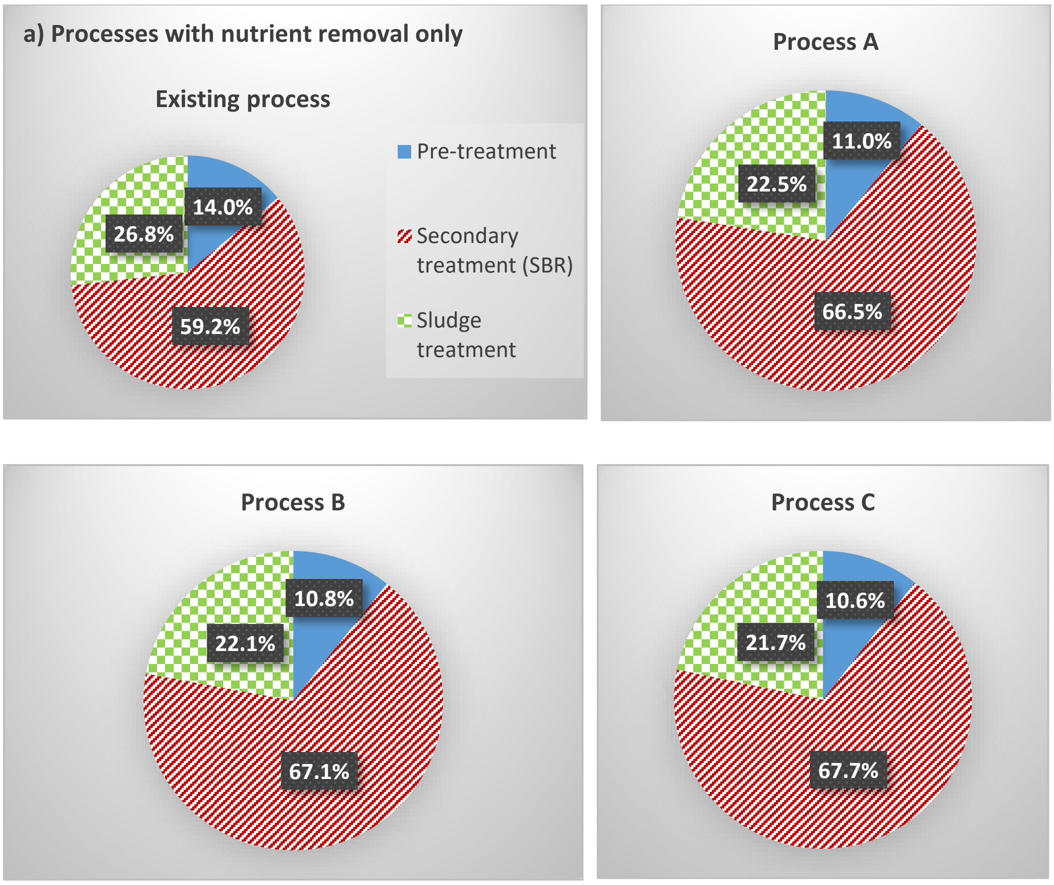


Figure S2. Cyclic operation design for SBRs operation in the three upgraded processes with nutrient removal. Note: A) Cyclic operation of SBRs in Process A with EBPR and nitrification-denitrification (AOA); B) Cyclic operation of SBRs in Process B with phosphorus precipitation by ferric and nitrification-denitrification (post-anoxic); C) Cyclic operation of SBRs in Process C with AGS technology for simultaneous carbon, N and P removal.


a) Processes with nutrient removal only
Existing process
Pre-treatment
Secondary treatment (SBR)
Sludge treatment
14.0%
26.8%
59.2%
Process A
11.0%
22.5%
66.5%
Process B
10.8%
22.1%
67.1%
Process C
10.6%
21.7%
67.7%

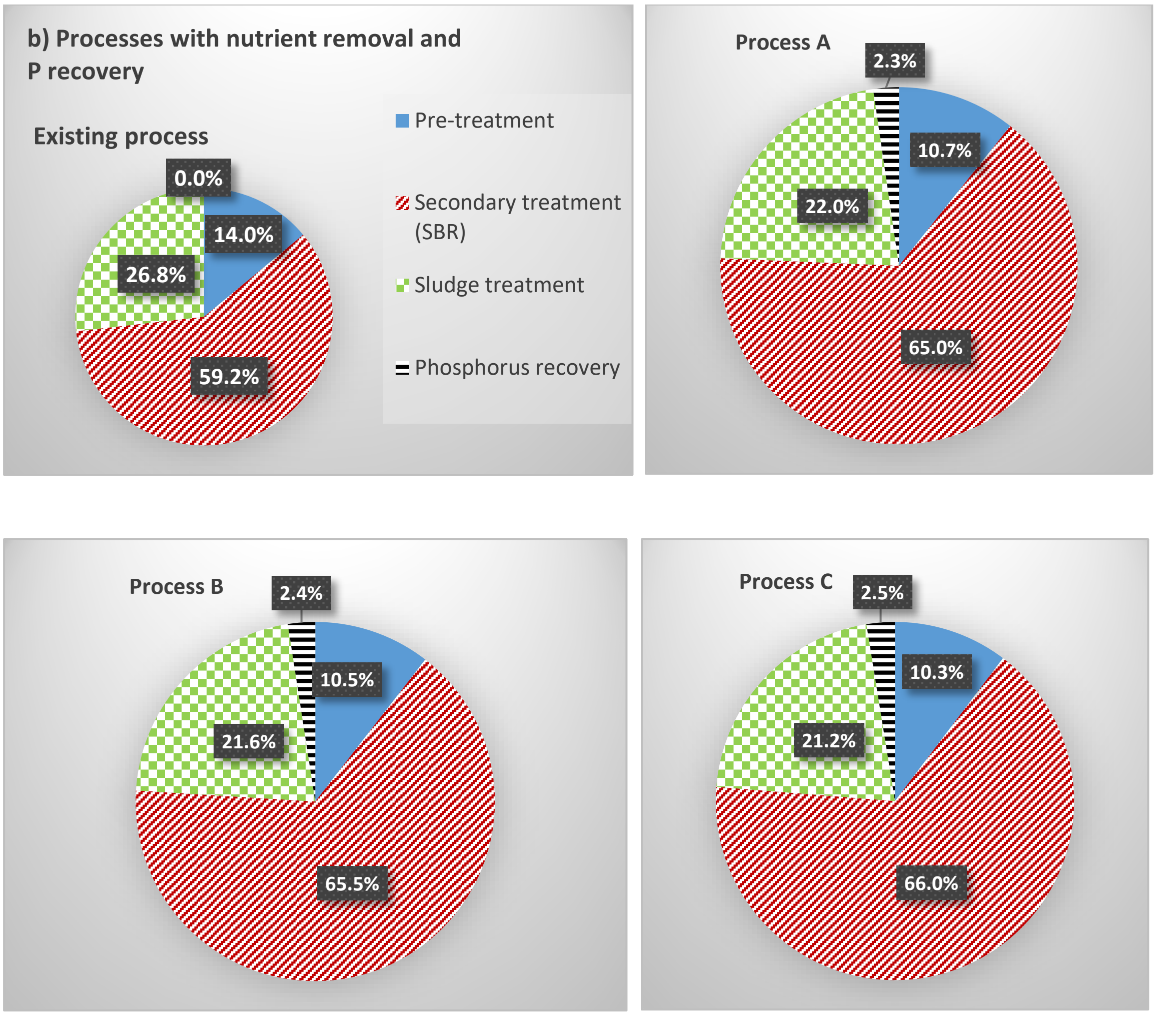


Figure S3. Hotspot analysis of the existing process and the three upgraded processes in terms of electricity consumption with: a) Scenario 1: three upgraded processes with nutrient removal only, and b) Scenario 2: three upgraded processes with both nutrient removal and phosphorus recovery.

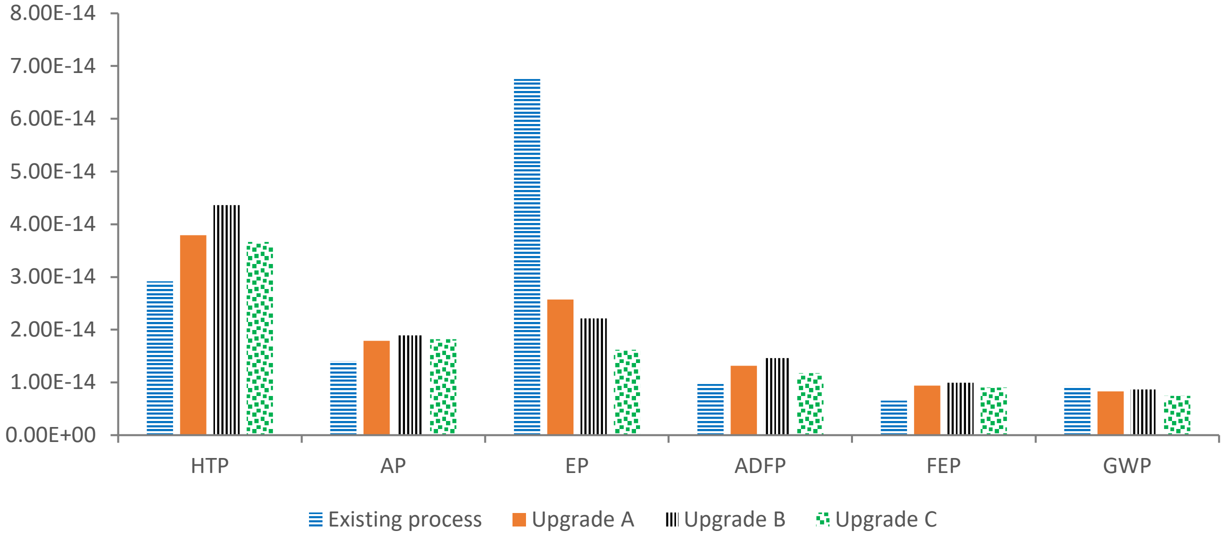


Figure S4. The comparison of environmental impact values between the existing process and the three upgraded Processes A, B and C using FU1 (1 m^3 of treated wastewater). Note: (HTP-human toxicity potential, AP-acidification potential, EP- eutrophication potential, ADFP-abiotic depletion (fossil fuel) potential, FEP-freshwater ecotoxicity potential, and GWP-global warming potential).