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# Life-cycle greenhouse gas emission analysis for integrated sewage sludge and food waste management strategy

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**ABSTRACT**

A comparative life-cycle greenhouse gas (GHG) emission analysis between a proposed integrated sewage sludge (SS) and food waste (FW) management strategy and business-as-usual scenarios in Singapore was performed in this study. The proposed approach was derived based on the design of co-located water reclamation plant and waste-to-energy incineration plant in Tuas, in which the SS and FW are anaerobic co-digested. The ratio of SS and FW was selected to be 1:1 for optimal biogas production. The effects of the power substitution and methane production rate uncertainties were investigated. The life-cycle GHG emission results show that the proposed strategy has a 64.3% reduction when compared to the current SS and FW treatments, or a 2129 tonnes $CO_2$-eq reduction potential per year.

**Keywords:** anaerobic co-digestion; sewage sludge; food waste; LCA; Greenhouse gas emission.

## 1. INTRODUCTION

As the water demand continuously increases in tandem with economic and population growth, the sewage sludge (SS) treatment becomes an environmentally sensitive problem. Anaerobic digestion (AD) is widely used in water reclamation plants (WRP), which can reduce the SS volume and produce biogas for power generation. However, the low C/N ratio of SS leads to a low biogas production rate [1] and the power generated from biogas engine can only offset about 30-50% percent of total WRP consumption [2, 3]. AD is also a crucial treatment for food waste (FW), as the protein, lipid and carbohydrate are effective feedstock for biogas production. However, the high organic matters and C/N ratio lead to acid inhibitions [4]. By balancing the C/N ratio and nutrient distribution, the anaerobic co-digestion of SS and FW has been shown to have synergistic effects of enhanced biogas production and solid residue reduction in both laboratory and full-scale studies [2, 5-7].

To assess the environmental impact of the integrated SS and FW management strategy on climate change, life-cycle greenhouse gas (GHG) emission analysis was performed in this work. The result of this work will identify the key process elements contributing to GHG emission and provide technical performance information for the governmental decision support systems of sustainable urban waste management.

## 2. LIFE-CYCLE GHG EMISSION ANALYSIS

### *2.1 Goal and scope definition*

The goal of the life-cycle GHG emission analysis was to compare the performance of the proposed integrated Singapore SS and FW management system. The ratio of SS to FW in the feedstock was selected to be 1:1 for maximum methane yield[2,8]. The functional unit was defined as the treatment of 400 tonnes of FW [8], which is the daily FW treatment capacity at the Singapore Tuas integrated waste management facility (IWMF), and 400 tonnes of SS. SS and FW management strategy to the current The SS is assumed to be generated from the domestic sector of Singapore WRPs, which consists of

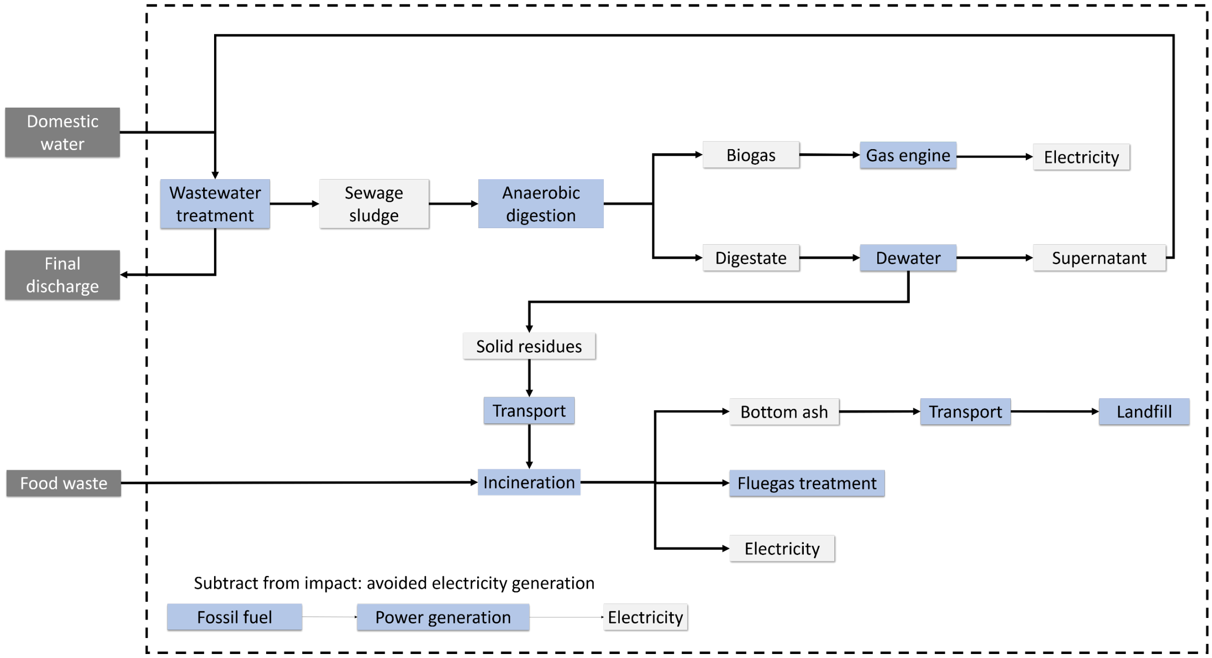



Figure 1. System boundary for the business-as-usual scenario of SS and FW management

8.2% moisture, 50.8% volatile, 15.2% fixed carbon and 25.8% ash [9]. The FW compositions were based on two Singapore representative food courts, which consists of 84 % organic fraction and 16 % impurities[5]. The total solids and volatile solids contents of the organic fraction are 22.9% and 18.0%, respectively. The impurities include 8.57% plastic, 3.34% carton, 1.91% metal, 1.21% glass, 0.81% textile and 0.11% wood.

The construction and manufacturing stages were not considered in this study due to the GHG emissions from the operation stage of these facilities and machinery dominates the life cycle GHG emissions [10]. The life-cycle GHG emission analysis was based on the 100-year model described in the Fifth Assessment Report by Intergovernmental Panel on Climate Change (IPCC AR5), according to the following equation:

$$Life\ cycle\ GHG\ emission\ \left[kg\ CO_{2-eq}\right]$$
$$= CO_2[kg] + 28 * CH_4[kg] + 265 * N_2O[kg]$$

### *2.2 Business-as-usual scenario*

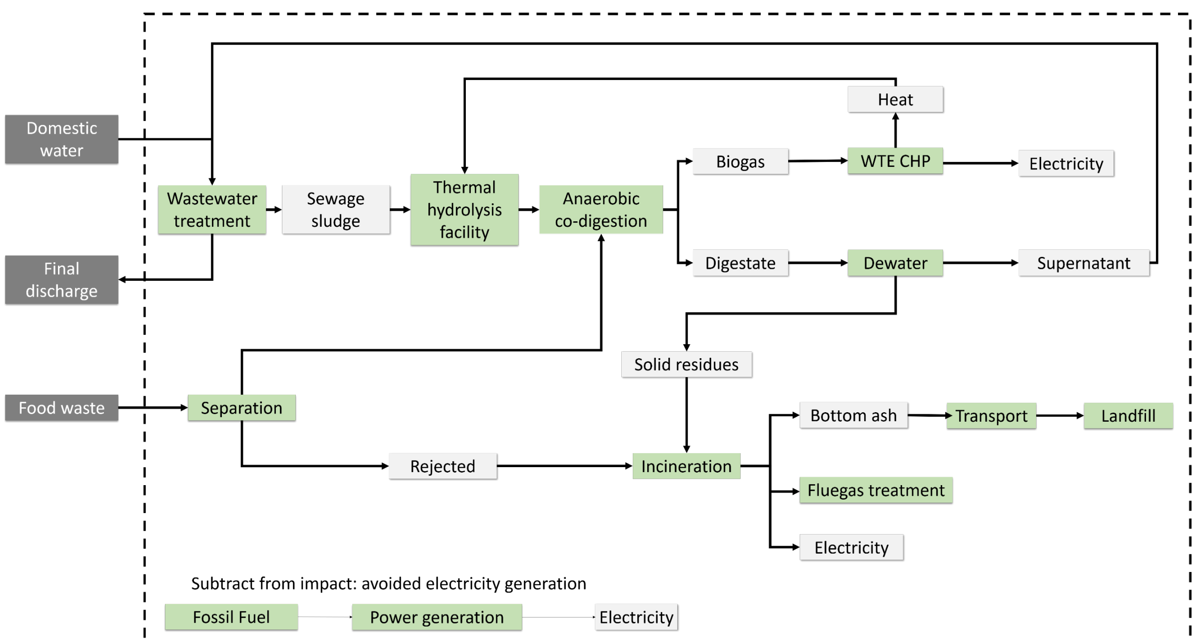



Figure 2. System boundary for the integrate SS and FW management strategy

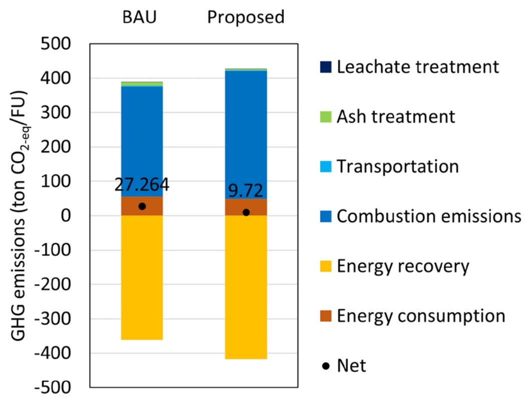


Fig 3 Life-cycle GHG emission analysis results of BAU and proposed scenarios

In the business-as-usual (BAU) scenario, as shown in Figure 1, the FW is incinerated in waste-to-energy (WTE) plant. The raw SS is produced from the domestic wastewater treatment and thickened in a centrifuge, which is treated after the preliminary, primary, and secondary treatment stages. The pretreated primary and secondary active sludge are employed as the feedstock of the AD unit. The digestate is then dewatered and transported for incineration in WTE plant, and the supernatant is sent back for water treatment together with the incoming water. The biogas generated from the AD is employed in biogas engine for power generations. The dried sludge, with a moisture content of approximately 10%, is transported to the WTE plant for incineration.

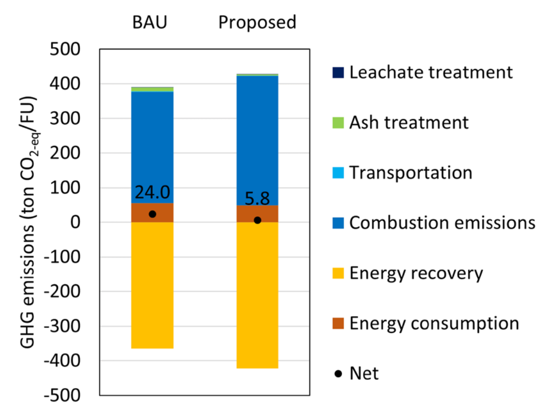
### *2.3 Proposed integrated SS and FW management strategy*

In the proposed integrated SS and FW management strategy, the WTE plant is designed to be co-located to the WRP. The FW is first separated by a screw-press pretreatment. The rejected impurities are sent for incineration, and the biomass slurry is employed as the feedstock together with the pretreated SS for anaerobic co-digestion. The raw sludge is then pretreated in a thermal hydrolysis unit for better digestion performance. The biogas generated from the anaerobic co-digestion unit is employed as the fuel for the external superheater to increase the steam parameters of the WTE boiler from 440 $^{o}$C/50 bar to 480 $^{o}$C/50 bar [8]. The steam recovered from the WTE combined heat and power generation system is used to offset the thermal hydrolysis energy consumption. As the generated electricity can directly connect to the WRP, there will be no requirements for dry SS transportation to WTE incineration plant.

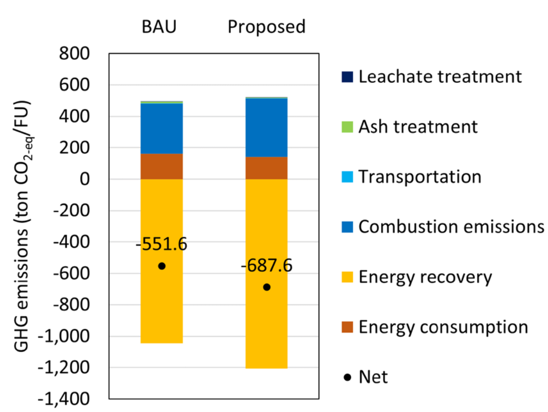
## 3. RESULT AND DISCUSSION

As shown in Figure 3, the life-cycle GHG emission of the proposed integrated SS and FW management is 9.72 ton $CO_2$-eq for the treatment of 400 tonnes of SS and 400 tonnes of FW, which represents a 64.3% reduction when compared to the BAU scenario. It can be found that the combustion emission and energy recovery (avoided electricity generation) are the two most significant elements of GHG emission. In 2019, the total water demand of Singapore is 430 million gallons per day, of which 45% is domestic water demand [11]. The treatment of domestic wastewater generates about 48530 tonnes of sewage sludge. If the proposed integrated SS and FW management strategy is applied to handle all the sewage sludge generated by the domestic wastewater treatment together with the same amount of FW, there will be a 2129 tonnes $CO_2$-eq reduction per year when compared to the current Singapore SS and FW treatments.

The avoided electricity generation (i.e. energy recovery or power substitution) is one of the key elements in the GHG emission results. In the life-cycle



a. Natural gas combined cycle



b. Coal-fired power plant

Fig 4. Life-cycle GHG emission analysis results based on different power substitutions

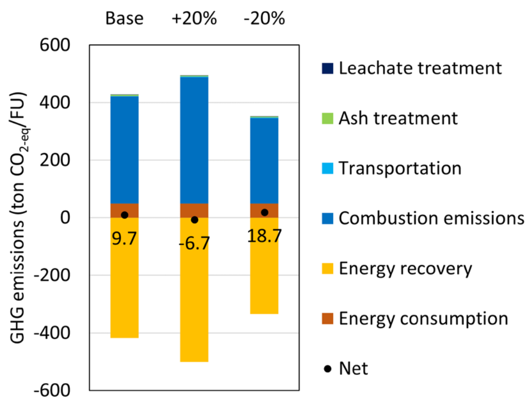



Fig 5. Life-cycle GHG emission analysis results based on methane production rates

GHG emission analysis shown in Figure 3, it is assumed that electricity generated from the sustainable waste management system replaces the general Singapore electricity, which is 0.4188 kg $CO_2$-eq/kWh. Two other different types of electricity derived from fossil fuels are considered in the sensitivity analysis: i) natural gas combined cycle, which is 0.4233 kg $CO_2$-eq/kWh; ii) coal-fired power plant, which is 1.211 kg $CO_2$-eq/kWh. As shown in Figure 4, a significant amount of GHG emission can be avoided based on the coal-fired power plant in both the BAU and proposed scenarios. The differences between the natural gas and general Singapore electricity are insignificant, which is due to the majority of Singapore electricity is from natural gas-based power plant.

The methane production rate from the digester is considered for sensitivity analysis, due to the variability of the organic content within the feedstock (food waste and dried sludge). To analyze the potential influence on the results of the life-cycle GHG emission calculation, two scenarios are considered for methane production rate, namely (i)-20% and (ii) +20% of the base-line production rate. These assumptions are in line with earlier studies on possible variations in methane production in digesters [12].

## 4. CONCLUSIONS

In this study, a comparative life-cycle greenhouse gas (GHG) emission analysis between a proposed integrated sewage sludge (SS) and food waste (FW) management strategy and business-as-usual scenarios in Singapore. The proposed approach was derived based on the design of the co-located water reclamation plant and waste-to-energy incineration plant in Tuas, in which the SS and FW are anaerobic co-digested. The life-cycle GHG emission results show that the proposed strategy has a 64.3% reduction, or a 2129 tonnes $CO_2$-eq reduction potential per year when compared to the current SS and FW treatments. The proposed integrated SS and FW illustrates a more environmental-friendly solution for urban waste treatment in other high-density Asian cities.

## ACKNOWLEDGEMENT

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