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Towards Sustainable Reuse of Gas-To-Liquid Biosludge for Industrial Crops Production

Sarah Y. Alnouri[a], Dhabia M. Al-Mohannadi[a,*], Debalina Sengupta[b,c]

[a] Chemical Engineering Program, Texas A&M University at Qatar, Education City, Doha, Qatar
[b] Gas and Fuels Research Center, Texas A&M Engineering Experiment Station (TEES), College Station, Texas, United States
[c] Energy Institute, Texas A&M University, College Station, TX, United States
dhabia.al-mohannadi@qatar.tamu.edu

As the world moves to achieve sustainable development goals (SDG) by 2030, the search for economic ways of waste recovery is becoming a priority in the growth of any economy. Qatar, an arid land and the home of a heavily active oil and gas industry, is a producer of large amounts of wastewater, greenhouse gas emissions and large consumer of fertilizers. Industrial biosludge results as a waste product of the wastewater treatment process. The use of industrial biosludge as organic fertilizer can help restore arable land and create symbioses across sectors. Thus, the aim of this paper is to create synergy by reusing wastewater and biosludge as a soil enhancer for industrial crop production. Industrial cash crops are non-food crops used in the manufacturing industry, such as cotton, rubber, etc., that typically compete with land needed for food production. The trade-off becomes more significant when dealing with an arid region with limited water and land resources such as Qatar. Therefore, this work introduces agricultural sustainability indicators to select the best industrial crop to grow in arable land. The most feasible crop to grow will be chosen based on a systems analysis. The analysis is carried based on the system interaction between the sludge, wastewater, energy, land, and crop production. A case study of the gas-to-liquid (GTL) industrial biosludge is analyzed using the method to demonstrate its effectiveness.

1. Introduction

The United Nations (UN) adopted the sustainable development goals (SDG) in 2015. Most of the goals aim to efficiently use resources, encourage re-use of materials, reducing emissions, and conserving resources for future generations. The chemical and petroleum industries have been actively growing, and as a result, there has been an increasing waste. This waste can be separated and re-used if there is a market, and it meets environmental and quality limits. Wastewater treatment, which is a part of many industrial application, is well understood process that generates treated water and a by-product of biosludge. Biosludge is a solid slurry of waste produced from industrial processes and wastewater treatment (Mostafa, 2015) that contains carbon, oxygen, nitrogen, and other trace materials. Circularity can be introduced by reusing this unwanted waste from the process industry in agriculture applications. The integration can help harsh climate arid regions by reusing wastewater and reduce fertilizer use. The focus is limited to industrial non-food cash crops such as fibres, rubbers, agrochemical etc. The use of biosludge as a soil enhancer is restricted to grow industrial crops in marginal soil to avoid 1) competing with limited suitable land for food production, and 2) contaminating the food chain with toxins. Waste resources reuse is part of sustainable progress goals and it can be presented in combinations of conversion routes that transform raw materials into value added products (Ahmed et al., 2020). In process systems engineering (PSE), many methods were developed on the Food-Energy-Water Nexus (FEW). Wan et al. (2016) explored the Malaysian sago industry using the Fuzzy multi-footprint optimization (FMFO). Rajakal et al. (2020) used a fuzzy-based method to arrange and expand agricultural lands sustainably value chain. Accorsi et al. (2015) proposed a multi-disciplinary linear programming method to combine localized and large-scaled allocation problems of agriculture. Nie et al. (2018) used a family of adaptable models with a mixed-integer nonlinear programming model that incorporates FEW to make economic decisions. Radmehr et

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al. (2020) used a Multi-Criteria Decision-Making (MCDM)-nonlinear programming approach that focuses on groundwater, energy, and food nexus. Hayati et al. (2010) used in sustainable indicators to improve the components of sustainability. Many works have been carried on the food-energy-water nexus and water networks, with little focus on both industrial crops and industrial process waste synergy. This work will be the first to 1) integrate biosludge and wastewater reuse with growing industrial crops and, 2) find the cost optimal industrial crop from a group of candidate.

An approach is developed based on the three elements in the Crop-Water-Energy (CWE) interactions following Figure 1. The method aims at determining cost optimal crop is suitable to grow within the available system by comparing sustainability performance. Four industrial crops were evaluated using this model in the case study: cotton, jute, sisal and kenaf. The biosludge was restricted to direct reuse. The main objectives of this study are: (1) to acquire an economical and sustainable plan for the production of industrial crops by developing a strategy to transition plants to make the land richer with nutrients; (2) to apply the model to the sustainable use of wastewater and biosludge produced by the GTL process plants.

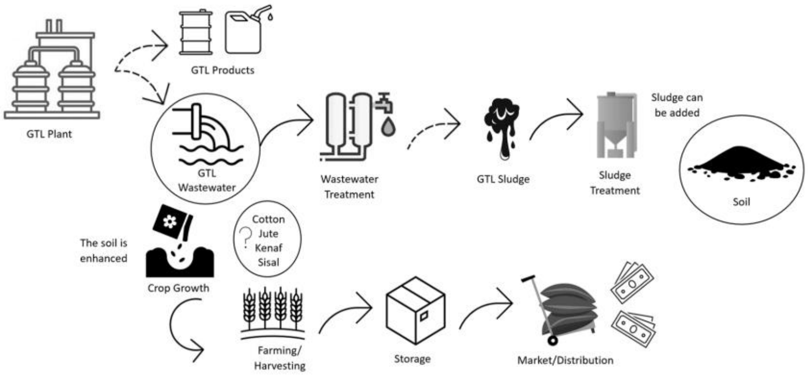

Figure 1: Crop value production chain.

2. Mathematical optimization model

A mathematical optimization model is established based a cost analysis that takes into account the interaction between crop revenue and crop cost. The focus of the work is to find the cost optimal industrial crop suitable to grow in defined plot of land and to understand the revenue streams, water, and nutrient allocation through a cost comparison. The model was developed to assess the interaction between the different aspects that make up the cost of a certain crop by interlinking elements in the CWE nexus. The objective of the model developed was to minimize the cost of growing a certain crop i (cotton: c, jute: j, sisal: s, kenaf: k). Eq(1) shows the objective function, which is the total cost. The total cost is calculated by introducing four sections: the energy (fertilizer) cost, the water cost, the land cost, the carbon tax, and the revenue. Eq(1) was coupled with constraints on the water demand, fertilizer import and production capacity. The constraints were decided upon the most sustainable limits applied on the data values available for each of the water, fertilizer, and production.

$$\begin{aligned} Total\ cost = {} & fertilizer\ cost + wastewater\ treatment\ cost + land\ cost + carbon\ tax \\ & - Revenue\ from\ selling\ crops \end{aligned} \quad (1)$$

The constraints on production capacity within minimum and maximum limits are shown in Eq(2).

$$Minimum\ production\ capacity \leq Crop\ production\ capacity \leq Maximum\ production\ capacity \quad (2)$$

Similarly constraints on the fertilizer import were based on limits on the nutrients Nitrogen (N), Phosphorous (P) and Potassium (K) and is generally described in Eq(3).

$$Minimum\ nutrient\ requirement\ for\ each\ crop \leq Nutrient\ supplied\ to\ crop \quad (3)$$

The total nutrient supplied to the crop is the sum of the imported fertilizer and the nutrient that was supplied to the soil from the biosludge/soil mixture as shown in Eq(4).

$$Imported\ nutrient\ + Nutrient\ in\ soil\ = Nutrient\ requirement \quad (4)$$

Subsequently water constraints were also executed as shown in Eq(5). The water flow was confined by the accessible minimum and maximum flow for each water type.

$$Minimum\ water\ type\ available\ \leq Water\ flow\ \leq Maximum\ water\ type\ available \quad (5)$$

A balance was set on the total water flow that is allowable to use for each individual crop in Eq(6).

$$\begin{aligned} &Treated\ process\ water\ + Treated\ sewage\ effluent\ + Groundwater\ + Freshwater \\ &\qquad = Water\ requirement\ of\ crop \end{aligned} \quad (6)$$

More constraints can be added to explore different scenarios such as cost reduction, carbon footprint minimization, wastewater reuse and land restoration. Figure 2 illustrates the super structure of the model, with the specific water types available. The structure begins with the wastewater treatment, resulting from industrial processes; that is if the water type given requires a specific treatment before entering the system. The biosludge coming from the wastewater treatment is mixed with the fertilizer and is combined with each of the nutrients in the fertilizer, Nitrogen, Phosphorous and Potassium, that are to be supplied to the crops. These water and energy inputs play huge parts of the model, providing the necessities for each crop to grow. They are restricted by constraints that represent the water and fertilizer demand collected as data. One of the crops shown in Figure 2, will be chosen to grow and as a result, emissions, waste, and by-products will accompany the end-use products go to the market stage

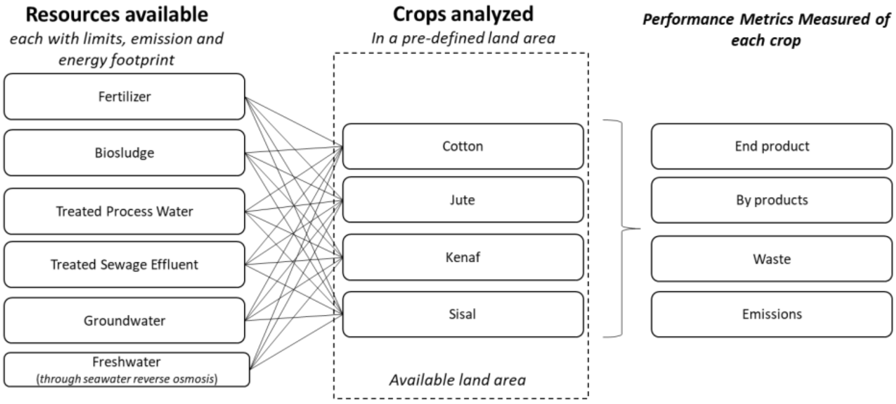

Figure 2: Crop agri-production structure.

3. Case study

Four water supply options were available for crop irrigation: desalinated water/freshwater (FW), treated wastewater (TWW), groundwater (GW), and treated sewage effluent (TSE). Table 1 below shows the maximum allowable regulation limits for irrigation in the first row and each of the water supply properties. Biological oxygen demand (BOD), COD, total dissolved solids (TDS), and total suspended solids (TSS) are compared to see which of them meets the standard regulations. According to the directive on the treatment of urban wastewater in Qatar, discharged sludge is required to meet a maximum BOD of 25 mg/L, a COD of 125 mg/L and TSS of 60 mg/L (CEC, 1991). The pre-TWW contaminants exceeded the limit reported in the first row, so it was excluded from the model's water inputs and all industrial wastewater was forced to be treated as outlined in Table 2.

Table 2 shows the cost of water treatment units, their energy consumption and carbon footprint due to the energy use. The emission factor per kWh assumed CO_2 emissions resulting from using natural gas at 60% power electricity of 0.413 kg CO_2/kWh (U.S. Energy Information Administration (EIA), 2020). Each of the processes listed below can remove certain contaminates, thus each treatment unit was given as option to remove contaminates from each water type. Reverse osmosis (RO) is the process that desalinates seawater into freshwater, which eradicates bulky, non-polar, ionic toxic contaminants. Whereas ultraviolet disinfection (UV) and submerged ultrafiltration are both used in the treatment of GTL wastewater to achieve a suitable TWW; UV disinfects the wastewater by eliminating microorganisms like bacteria and viruses and ultrafiltration (UF) removes particles sized from 0.02 µm to 1 nm (Gupta et al., 2012). Sewage treatment (ST) is the treatment of sewage and it includes UF and RO along with another stage of treatment called chlorination (Cl$_2$) and that is the last step before reaching the purified water or TSE (Alhumoud and Madzikanda, 2010).

Biosludge-soil mixture was given as an option to provide nutrients with fertilization. The biosludge selected is derived from green waste and is applied directly to the soil. The soil mixed with 12% biosludge was presumed to have nutrients, N, P and K (Kogbara et al., 2020). Fertilizer can be imported to supply extra nutrients if needed. Table 3 summarizes known constraints and requirements of factors in the revenue, water balance, and fertilizer balance. Selling prices are varying parameters, so two ends were picked as the high and low-price cases. Water and nutrient demands are also a very important aspect of their respective balance. More values were gathered in Table 4 where each nutrient of the fertilizer was assigned a price from (Quinn, 2021). The respective energy required and CO$_2$ emissions stemming from the application, processing and transportation was taken from (Lahlou et al., 2020).

Table 1: The concentrations of the different types of water available compared to the maximum allowable limit.

Type of water	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	TSS (mg/L)	Reference
Regulation Maximum limit	30	150	1750	50	(Lahlou et al., 2020)
Fresh Water (FW)	6	10	500	0	(Gupta et al., 2009)
Treated process wastewater (TWW)	-	30[a]	515.15[b]	-	(Veolia Water Solutions & Technologies, 2013[a]), (Enyi et al., 2013[b])
Ground Water (GW)	0	0	2420	-	(Planning and Statistics Authority, 2018)
Total Sewage Effluent (TSE)	1.7	8.7	1005	1.9	(Lahlou et al., 2020)

Table 2: The cost of the wastewater treatments, their energy consumption, and subsequent CO$_2$ emissions.

Wastewater Treatment Type	Cost (\$/m^3)	Energy Consumption (kWh/m^3)	CO$_2$ Emissions (kg CO$_2$/m^3)	Reference
ST (UF+RO+Cl$_2$)	0.591	6.0	2.478	(Bhojwani et al., 2019)
UV	0.018[c]	0.4[d]	0.1652	(Bhojwani et al., 2019[c]), (Rott et al., 2018[d])
UF	0.270[e]	1.0[f]	0.4130	(Tran et al., 2016[e]), (Jasim et al., 2016[f])
RO	0.300	5.0	2.065	(Bhojwani et al., 2019)

Table 3: Nutrient requirements and price range of crops from (Dunne et al., 2016[g]) and (Wenger et al., 2018[h]).

Crop	Lower Price (\$/t)	Higher Price (\$/t)	Water demand (m^3/t)	N demand (kg/ha)	P demand (kg/ha)	K demand (kg/ha)	Reference
Cotton	1,700[h]	2,000[g]	507[i]	2[j]	0.34[j]	3.4[j]	(Alkhateeb, 2010[i]), (Bassett et al., 1970[j])
Jute	600[h]	900[g]	2,159[k]	70[l]	35[l]	70[l]	(Kundu, 2016[k]), (IndiaAgroNet, 2016[l])
Sisal	800[g]	2,400[h]	100[m]	326[n]	71[n]	0[n]	(Department of Agriculture, 2015[m]), (Hartemink, 1998[n])
Kenaf	400[h]	800[g]	0.21[o]	100[p]	40[p]	60[p]	(Danalatos and Archontoulis, 2010[o]), (Kamal, 2014[p])

Table 4: Nutrient prices, energy requirements, and CO$_2$ emissions of available fertilizers.

Nutrient Type	Price (\$/kg)	Energy requirements (kWh/kg)	CO$_2$ emissions (kg CO$_2$/kg nutrient)
Nitrogen (N)	0.344	20.5	10.3
Phosphorus (P)	0.642	4.9	1.5
Potassium (K)	0.423	3.8	1.9

4. Results

The mixed integer nonlinear program (MINP) was solved using What'sBest! 17.0" solver (LINDO, 2020). It was selected since it is a deterministic solver suitable for mixed integer nonlinear problems. The optimization model operated with binary constraints on the fertilizer, water, and crop production rates. Two solutions were obtained based on the lowest cost achievable to grow one crop out of the four choices. A study of two cases were analyzed to by applying sensitivity on the selling price for all crops. The prices variation of is shown in Table 3.

In case 1 of low-price end: cotton had performed the best, with \$ 62,620 profit that can be made per year. The production rate of cotton was 80 t/y, taken from (FAO, 2018), and it did not require any extra N, P or K fertilizer since the soil had already been provided the mixture of nutrients and biosludge. This resulted in zero energy and emissions from fertilizer-use. The water supply consisted of 50 m^3/d of TWW and 61.1 m^3/d of GW that equated the requirement 111.1 m^3/d. Table 5 highlights the key inputs and findings after running the model.

While in case 2 of high prices, sisal was the best performing crop with a total profit of \$ 1,152,300 per year. A production rate, F_s of 740 t/y, had additional fertilizer input of 321.5 kg/t of N, that consumed 6,591.2 kWh/t with a CO_2 emission of 3.31 t CO_2/t crop. The water input was 102.7 m^3/d of TWW and 100 m^3/d of GW which satisfied the minimum water requirement of 20 m^3/d. The water demand of sisal was only 100 m^3/t in comparison to cotton as recalled in Table 3. However, after the optimization sisal was more demanding than cotton in terms of the water use and that was due to its bigger production rate. Sisal also had a greater fertilizer demand overall as compared with cotton; that is the main reason of more CO_2 being produced from the addition of fertilizer.

Table 5: The crop chosen, production rate, water breakdown, N fertilizer, CO_2 emissions, and total profit.

Cases	Best crop	F_i (t/y)	TWW (m^3/d)	GW (m^3/d)	N fertilizer (kg/t)	CO_{2f} (t CO_2/t nutrient)	CO_{2w} (kg CO_2/m^3)	Total profit (\$/y)
1	Cotton	80	50	61.1	0	0	0.5782	62,620
2	Sisal	740	102.7	100	321.5	3.31	0.5782	1,152,300

5. Conclusions

It has always been difficult to counteract the damage that the environment has faced in the past century. The model developed is meant to diversify the methods and procedures planned for agriculture growth and waste recovery by creating easy pathways for meeting sustainability targets. The mixed integer nonlinear mathematical model was developed for the ease of decision-making on the best crop to harvest. The initiative was to create synergy between reusing industrial wastewater and biosludge and the production of industrial crops. A case study in the arid country Qatar was applied via the optimization model on the GTL wastewater and four industrial crops, cotton, jute, kenaf, and sisal. Two cases have been tested, case 1 for the low prices of the crops, while case 2 dealt with the high prices of them. The results were diverse, with cotton outperforming in low prices, while sisal outperforming in case 2. The total profit after optimizing the model to a minimum cost objective was \$62,621/y for cotton and \$1,152,300/y for sisal. The main findings that the results proved are: (1) the selling price of the crops greatly affects the cost analysis and decision; (2) the crop fertilizer and water inputs depend on the constraints. A limitation that will be addressed in future works is the addition of multiple objectives and the full supply chain consideration including harvesting, distribution and transportation. This aids in expanding the sustainability complexity that the model can provide.

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