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Optimal Synthesis of Dairy Industry Sludge

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Dairy industry discharges sludge contains a high concentration of organic compounds and suitable for the production of various kinds of value. The optimisation and process improvement on individual processes of a sludge treatment can indeed reduce the waste treatment cost, and subsequently, improve the profit of the dairy industry. Yet by efficiently utilising the sludge to produce value-added products, the dairy industry can potentially gain extra profit. There is a need to develop a framework to screen and synthesise the optimal process pathways for the sludge from the dairy industry. This work presents a Mixed Integer Non-Linear Programming (MINLP) model to obtain the optimal utilisation and selection of the processing route for dairy industry sludge subject to maximise the profitability of value-added product, by considering the revenue of value added product, total processing costs and capital cost of thickening, dewatering and processing technology, and the transportation cost of dewatered sludge to by-product processing industry. The difference between the new optimal route and the baseline case study were highlighted with the impacts of the economic performance on the fluctuation of the mixed sludge volume.The result of optimisation model shows that the maximum profit can be achieved is 31,789 MYR/month while the total variable cost can be reduced from 185,800 MYR/month to 87,407 MYR/month which is reduced by 52.96 % as compared to the baseline case. Vermicomposting was found to be the optimal choice of processing technologies due to the high profitability.

1. Introduction

The large volume of sludge produced from wastewater treatment in dairy industry coupled with environmental pressure and the stringent sludge regulations of reuse or dispose (Cieślik et al., 2015), remain the problematic issue in achieving sustainable sludge management. Although sludge represents only 1 % to 2 % of the treated wastewater volume, the management is highly complicated in term of the treatment and processing technologies and has a cost usually ranging from 20 % to 60 % of the total operating costs for the wastewater treatment plant. To reduce the total variable cost emerge, the industry can explore the option of optimally utilising the sludge to produce value-added products by selecting a suitable sludge treatment and processing. As consequences, the disposal cost of sludge into the landfill and incinerator is expected to minimise (Spinosa, 2011) and the dairy industry can earn profit from the value-added products.

In general, sludge consist more than 95 % of water and must undergo various treatment processes such as preliminary operations, thickening, stabilisation, conditioning, dewatering, heat drying, and thermal reduction, before its reuse or final disposal (Kelessidis and Stasinakis, 2012). The removal of water content is a fundamental unit operation for the reduction of the sludge volume to be treated or disposed. In sludge processing phase, water removal takes place in thickening and dewatering stages. Gravity thickeners are most commonly used for sludge thickening, while the types of dewatering machines most commonly applied are rotary drum vacuum filters, filter presses, belt presses, and decanter centrifuges (Foladori et al., 2010). Few studies have been examined on the optimisation and the cost of the sludge processing technology. Boráň et al (2010) conducted a numerical experiment on the impact of the consumption of flocullant for the quality of dewatered sludge which resulted the decrease in the cost of the sludge processing technology. In contrast, Olajire et al. (2009) evaluating a broad aspect considered the logistic problem in order to minimise the cost incurred in sludge management until final disposal by using mathematical linear programming model (LP). However, the works doesn't consider the utilisation of the value-added products from the sludge processing route. It has been noted that by efficiently utilise the sludge to produce value-added products, the industry can potentially gain extra profit. Meanwhile, a few researches highlighted on the utilisation of the by-products of sludge in the individual processes as such the production of biogas (Pilarska et al., 2016), vermicompost (Anusha and Paul, 2015) and bioplastic (Roland-Host et al., 2013). Therefore, in this work, the development of an optimisation model from the dairy industry sludge is proposed with the objective function to minimise the total variable cost while selling these value-added products. To reduce the total variable cost emerge, this works explore the option of optimally utilising the sludge to produce value-added products by selecting a suitable sludge processing route.

2. Methodology

There are few steps in determining the optimal solution of dairy industry sludge which involves the extraction data, superstructure development, mathematical formulation, coding (optimisation is performed using General Algebraic Modelling System (GAMS) software) and sensitivity analysis. In following sub-sections, the superstructure and the general mathematical formulation of the proposed model are presented. Depending on the case study, the model can be applied to solve the sludge planning for other industries as well.

2.1 Superstructure development

Figure 1 illustrated the superstructure in determining the optimal processing route of dairy industry. The box denotes the wastewater treatment plant *i,* the dotted boxes denote the sludge treatment or processing units which are thickening technology *m*, dewatering technology *n* and processing technology *j* while the lines denote the processing routes. The circle represents the value-added product *p* and the box denotes the final disposal *k*. There are several treatment technologies available for sludge thickening (screw thickener, drum thickener, belt thickener and etc.) and for sludge dewatering (decanter, chamber filter press, membrane filter press, belt filter press and etc.). The treated sludge can be utilised into a value-added product *p* (vermicompost, biogas, bioplastic) by sludge processing technology *j* (vermicomposting, anaerobic digestion, aerobic dynamic feeding)

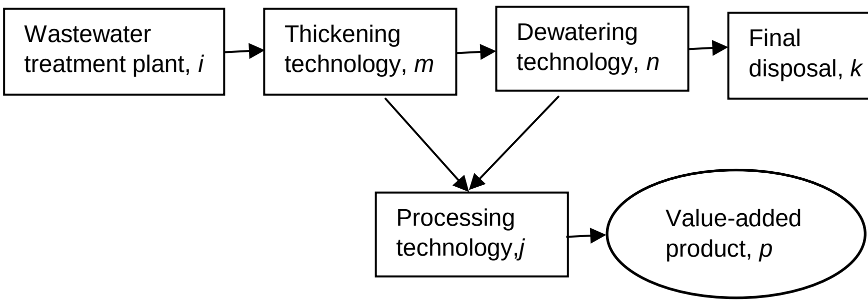

Figure 1: Sludge processing route

2.2 Model formulation

The objective function consists of revenue (*REV*), total processing cost (*TPCOST*), total capital cost (*TCCOST)* and total transportation cost (*TTCOST*). The aim is to maximise the overall profit as given in Eq(1). The term *REV* in Eq(2) refers to the revenue of value-added product gained from utilisation of dairy sludge. PRO_p denotes the production rate of value-added product *p*. $PRICE_p$ denotes the unit selling price for value-added product *p*.

$$PROFIT = REV - TPCOST - TCCOST - TTCOST - DCOSTk \quad (1)$$

$$REV = \sum_p PRICE_P \times PRO_P \quad (2)$$

The term *TPCOST*, represents the total processing cost and production cost involved the processing cost of thickening technology *m*, the processing cost of dewatering technology *n* and the production cost of value-added products through corresponding technologies. X_{im} represents the incoming volume of mixed sludge form wastewater treatment plant *i* supplied to the thickening technology *m* and Y_{mn} represents the incoming volume of thickened sludge form thickening technology *m* supplied to the dewatering technology *n*. The $AASP_j$ refers to the available amount of sludge (dry basis) for the processing technology *j* The term *DTS* and *DDS* are the density of thickened and dewatered mixed sludge respectively. The term $DSFT_m$ and $DSFD_n$ are the dry solid fraction of thickened and dewatered sludge. Finally, $UPCOSTt_m$, $UPCOSTd_n$, and $UPCOST_j$ converts the dry solid equivalent of sludge into monetary value.

$$TPCOST = \sum_{im} X_{im} \times DTS \times DSFT_m \times UPCOSTt_m + \sum_{mn} Y_{mn} \times DDS \times DSFD_n \times UPCOSTd_n + \sum_j AASP_j \times UPCOST_j \quad (3)$$

The term *TCCOST* represents the total capital cost of processing technologies shown in Eq(4). The term CPT_m,CPD_n and CPP_j converts the volume and dry solid equivalent of sludge into monetary value.

$$TCCOST = \sum_{im} X_{im} \times CPT_m + \sum_{mn} Y_{mn} \times CPD_n + \sum_{jp} AASP_j \times CPP_j \quad (4)$$

The term *TTCOST* represents the total transportation cost involved transportation cost of: a) thickened sludge (wet sludge) between dairy plant *i* and by-product processing plant *j*, b) dewatered sludge (wet cake sludge) between dairy plant *i* and by-product processing plant, c) transport cost of dewatered cake sludge between dairy plant *i* and final disposal *k* . The term VTS_j indicates the volume of thickened sludge enter to the processing technology *j* and $TCAPC_i$ represents the truck capacity at dairy plant *i* and $DIST1_{ij}$ represents the distance between dairy plant *i* and by-product processing plant *j*. The term VDS_j indicates the volume of dewatered sludge enter to processing technology *j* and $DIST1_{ij}$ represents the distance between dairy plant *i* and by-product processing plant *j*The expression *AVDFj* represents the volume of dewatered sludge disposed via final disposal *k* (landfill) and $DIST2_{ik}$ represents the distance between dairy plant *i* and final disposal *k.*

$$TTCOST = \sum_{ij} VTS_j \times \frac{(R1 \times TCAPC_i) + (R2 \times DIST1_{ij})}{TCAPC_i} + \sum_{ik} VDS_j \times \frac{(DIST1_{ij} \times R2)}{TCAPC_i} + \sum_{ik} AVDF_j \times \frac{(DIST2_{ik} \times R2)}{TCAPC_i} \quad (5)$$

As shows in Eq(6), *DCOST* indicates the disposal cost of dewatered sludge at final disposal. The inner summation represents the incoming volume of dewatered sludge form dewatering technology *n* transferred to the final disposal *k*. The terms of *DDS* and $DSFD_n$ converts the volume of sludge into dry solid equivalent kg and the term $UDCOST_k$ converts them all into a monetary value.

$$DCOSTk = \sum_{nk} Z_{nk} \times DDS \times DSFD_n \times UDCOST_k \quad (6)$$

2.3 Constraint

The available volume of thickened sludge after thickening technology *m* either send to dewatering technology *n* or processing technology *j* . The utilisation of thickened sludge expressed in the Eq(7)

$$AVTS_m = \sum_n Y_{mn} + \sum_j D_{mj}\ , \qquad \forall m \in M \quad (7)$$

The available volume of dewatered sludge after dewatering technology *n*, is either send to processing technology *j* or disposed of via final disposal *k.* This relation is expressed in the Eq(8). The available volume of sludge from thickening technology *m* and dewatering technology *n* feed to processing technology *j* can be formulated using the Eq(9).

$$AVDS_n = \sum_j Q_{nj} + \sum_k Z_{nk}\ , \qquad \forall n \in N \quad (8)$$

$$AVSP_j = \sum_n Q_{nj} + \sum_m D_{mj}\ , \qquad \forall j \in J \quad (9)$$

The term $MC1_m$ and $MC2_n$ represent the achieved moisture content through thickening technology *m* and dewatering technology *n.* Meanwhile, the variable $MCspec1_j$ denotes the moisture content specification for processing technology *j.* The relation is shown in the Eq(10). The term $MC2_n$ represents the achieved moisture content through dewatering technology *n.* Meanwhile, the variable $MCspec2_k$ denotes the moisture content specification for final disposal *k.* The relation is shown in the Eq(11).

$$AVSP_j \times MCspec1_j = \sum_n Q_{nj} \times MC2_n + \sum_m D_{mj} \times MC1_m\ , \qquad \forall j \in J \quad (10)$$

$$AVDF_k \times MCspec2_k = \sum_k Z_{nk} \times MC2_n\ , \qquad \forall k \in K \quad (11)$$

The volume of mixed sludge supplied to thickening technology *m* is governed by the available volume of mixed sludge at wastewater treatment plant *i,* as expressed by Eq(12)*.*The available volume of mixed sludge at wastewater treatment plant *i* and the maximum capacity of mixed sludge produced by wastewater treatment plant formulated in Eq(13).

$$\sum_m X_{im} = AVMS_i \quad , \quad \forall i \in I \tag{12}$$

$$AVMS_i \leq CWWTP_i \quad \forall i \in I \tag{13}$$

The volume of mixed sludge supplied to thickening technology *m* and dewatering technology *n* are governed by the maximum throughput rate of thickening and dewatering technologies, as expressed by Eq(14) and Eq(15).

$$\sum_i X_{im} \leq MTRT_m \quad , \quad \forall m \in M \tag{14}$$

$$\sum_m Y_{mn} \leq MTRD_n \quad , \quad \forall n \in N \tag{15}$$

The term H_m, G_n and S_j are the binary variable involve in selecting only one technology for each thickening, dewatering and processing technologies, as shown in Eq(16) to (18). The sludge will not send to the thickening, dewatering and processing technologies if it is not adopted, as constrained by Eq(19) to Eq(21). The term *L* represents a big positive number.

$$\sum_m H_m = 1 \tag{16}$$

$$\sum_n G_n = 1 \tag{17}$$

$$\sum_j S_j = 1 \tag{18}$$

$$AVTS_m \leq (H_m \times L) \quad , \quad \forall m \in M \tag{19}$$

$$AVDS_n \leq (G_n \times L) \quad , \quad \forall n \in N \tag{20}$$

$$AVSP_j \leq (S_j \times L) \quad , \quad \forall j \in J \tag{21}$$

The product demand constraint is factored into the model via Eq(22), with $DEMPRO_p$ representing the maximum demand for product *i.*

$$PRO_p \leq DEMPRO_p \quad \forall p \in P \tag{22}$$

3. Case Study

In the baseline case, 1,000 m^3 of mixed sludge which consists of primary and secondary sludge generated from the wastewater treatment plant (conventional activated sludge system) at dairy industry in monthly basis. Typically, the sludge undergoes thickening and dewatering treatment to reduce the moisture content before transferred to the final disposal. Water is removed from the sludge to concentrate it from 2 % solids and 98 % water to 37.5 % solids and 62.5 % water. The landfill requires the dried sludge with high solid content more than 30 %. The distance between dairy plant and landfill is 44 km meanwhile the distance between the dairy industry and by-product processing industries of vermicompost, biogas and bioplastic plant are 29 km, 43 km and 39 km. The following comprise the key variables and parameter in the model:

a. Thickening technology *m* ;1 Screw thickener, 2 Rotary drum thickener, 3 Belt thickener, 4 Centrifuge
b. Dewatering technology *n* ; 1 Decanter/ Centrifuge, 2 Chamber filter press,3 Membrane filter press, 4 Belt filter press, 5 Screw press
c. Processing technology *j* ;1= Vermicomposting, 2= Anaerobic digestion, 3= Aerobic dynamic feeding
d. Unit processing cost of sludge processing technology of vermicomposting (Ahmed et al.,2013), anaerobic digestion (Arsova, 2010), aerobic dynamic feeding (Roland-Holst et al., 2013)
e. Unit processing cost for thickening consist of screw thickener, rotary drum thickener, belt thickener, centrifuge and dewatering technology consist of centrifuge, frame and plate filter press, membrane filter press, belt filter press, screw press (HUBER TECH.)
f. Capital cost of thickening and dewatering technology, and capital cost of processing technology (Composting Council of Canada, 2010)
g. Dry solid fraction flow out thickening and dewatering technology (ANDRITZ Separation)
h. Achieved moisture content through thickening and dewatering technology (ANDRITZ Separation)
i. Unit price for vermicompost (Anon, 2008), biogas (Murphy et al., 2004), bioplastic (Roland-Holst et al., 2013)
j. Yield conversion for vermicomposting (Gopinathan and Thirumurthy, 2012), anaerobic digestion (Arsova, 2010), aerobic dynamic feeding (Carletto et al., 2011)

4. Results and Discussion

The case study data was fitted into the developed MINLP model. From the baseline study, 21,499.87 kg of dry solid is disposed to landfill monthly. The total of variable cost incurred for the sludge treatment, transportation and disposal cost to the landfill is 185,800 MYR/month. Figure 2 indicates the new sludge processing route for the dairy industry. Based on the findings, vermicomposting is selected as the optimal processing due to high profitability as compared to others. The most optimal thickening technology is rotary drum thickener and the optimal dewatering technology is chamber filter press. The total amount of sludge processed by thickening and dewatering technology is 21,500 kg dry solid while, and amount of sludge converted to vermicompost is 14,899.50 kg. The selling of vermicompost generates a profit of 31,789 MYR/month and estimated profit margin is 26.67 %.

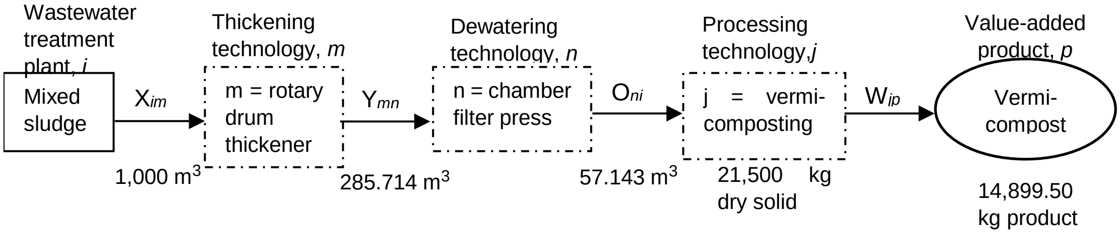

Figure 2: Optimal processing route of dairy industry sludge (monthly basis)

Table 1 shows the comparison between existing and new optimal processing route for the dairy industry. The percentage of reduction of total variable cost is 52.96 % compared to the baseline case. The processing cost and capital cost of thickening technology lessened by 70.75 % and 71.70 %. The processing cost and capital cost of dewatering technology decreased by 63.57 % and 60.59 %. There is reduction about 29.38 % in the transportation cost as compared to the baseline case. The case study shows that the potential monthly profit for an optimal processing route of dairy sludge is 31,789 MYR/month and revenue from selling the value-added product is 119,200 MYR/month.

Table 1: Comparison between existing and new processing route for the dairy industry sludge

Variable cost	Existing (MYR/month)	New (MYR/month)	Percentage of reduction (%)
Processing cost of thickening technology *m*	27,954	8,177	70.75
Processing cost of dewatering technology *n*	138.210	50,350	63.57
Processing cost of processing technology *j*	-	1,935	-
Capital cost of thickening technology *m*	5,300	1,500	71.70
Capital cost of dewatering technology *n*	2,900	1,143	60.59
Capital cost of processing technology *j*	-	16,770	-
Transportation cost of dewatered sludge	10,667	7,532	29.38
Disposal cost	753	-	-
Total variable cost	185,800	87,407	52.96
Revenue	-	119,200	-
Profit	-	31,789	-

To examine the effect of new optimal processing route, the sensitivity analysis is conducted on economic potential by adjusting ± 40 % increment and decrement volume of the mixed sludge. The increase volume of the mixed sludge shows the increasing cost of each processing route. Based from the observation, the highest is the capital cost of the thickening technology which increased by 56.67 %. 40 % increment in the volume causes the total variable cost increased by 35.06 %. It was found that the revenue fluctuates within the range of -18.18 % to 7.26 %. Note that, if the amount of generated product exceeds the minimum product demand, the excess volume of mixed sludge will be sent for final disposal.

5. Conclusions

A propose MINLP model indicate that an optimal processing route could be economically beneficial and reduce the total variable cost and maximise the profit from the sludge utilisation. The model could be extended to include other technology processing and disposal method as such drying and incineration.

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