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Synthesis of a Sustainable Wastewater Treatment Plant for Sago Industry using Fuzzy Optimisation

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Wastewater treatment plant (WWTP) is an essential process in the manufacturing industry. However, wastewater treatment process is not a profitable process as it requires a significant amount of investment. It is important to design a WWTP that meets wastewater discharge legalisation with low investment costs. To do this, area footprint (land area) occupied by technologies in a WWTP must be factored into the design decision. Unfortunately, the area footprint is yet to be studied. As wastewater treatment processes involve multiple treatment units, the different combinations of these treatment units will give a range of capital costs and costs associated with the area occupied. In addition, the carbon footprint of technology resulting from power consumption must be considered. Each technology possesses unique power consumption requirements and these requirements may influence the total carbon footprint for a given WWTP design. Investment costs, area footprint and carbon footprint must be considered simultaneously but are conflicting in nature. This work aims to present a multi-objective decision-making tool to screen wastewater treatment technologies and to synthesise a WWTP design with low investment cost, low area footprint, and low carbon footprint. Specifically, fuzzy multi-objective optimisation (FMOO) is used to determine a desirable trade-off between investment costs, area footprint, and carbon footprint. To demonstrate the developed approach, a sago-based WWTP case study is solved. Based on the results, a trade-off between these optimisation objectives had reduced 5.35 m^2 of area footprint, 986 USD/d of total investment cost, and 108 kg CO_2/d of carbon footprint of the synthesised WWTP.

1. Introduction

Sago industry is one of the major industries in Sarawak, Malaysia that generates a significant amount of organic wastewater (Yunus et al., 2014). According to Adeni et al. (2010), every 1 t of sago starch produced, approximately 10 t to 22 t of organic wastewater will be generated. This significant amount of wastewater produced requires proper wastewater treatment. A proper wastewater treatment process can be synthesised before actual installation and operation to avoid extra investment costs needed to rectify the process in the future. In this respect, there are several published research works had incorporated cost optimisation (Ho et al., 2019) and carbon footprint optimisation (Padrón-páez et al., 2020) of a WWTP. However, limited research works had considered area footprint (land area) as an important design criterion in synthesising a WWTP. Shortage of land area is an issue in some countries as the rapid development of cities and heavy industries had led to global deforestation issues. Malaysia for instance, had the world's highest rate of deforestation between year 2000 and 2012 (Butler, 2013). Consequently, authorised organisations and departments had implemented more stringent regulations to control the rate of deforestation, resulting in land prices in Malaysia to rise significantly for the past 10 y (WWF, 2020). The area footprint required to synthesise a WWTP is essential to be optimised as the land area cost of a WWTP contributes to a high capital cost. To optimise the area footprint of a WWTP, the size of equipment must be minimised. Nevertheless, smaller wastewater treatment technologies are usually more advanced technologies and require higher cost compared to conventional wastewater treatment technologies (Ang et al., 2019). In addition, smaller advanced technologies may consume higher power consumption, resulting in a higher carbon footprint (Fernandez-Dacosta et al., 2016). Due to the extensive

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selection of technologies, this becomes a challenge for industrial decision-makers to select the optimum wastewater treatment pathway which fits all the desired objectives while ensuring the discharge effluent complies with local discharge legislation. The combination of different technologies with various specifications will affect the performance, investment cost, and area footprint (land area) of the entire WWTP. In this respect, this work had employed fuzzy multi-objective optimisation (FMOO) in the developed mathematical model from this study. FMOO provides a trade-off between multiple optimisation objectives by integrating these objectives into a single parameter or degree of satisfaction, λ (Zimmermann, 1978). This method is useful to address the vagueness and ambiguity present in quantifying the target range of each optimisation objective while having more than one selection between the WWTP pathway alternatives. In this situation, FMOO is a better tool to solve multi-objective optimisation problems with uncertainty in identifying the importance or contribution of each optimisation objective (Pan et al., 2014). To illustrate the developed approach, this work aims to present a FMOO tool to synthesise an optimum sago biorefinery WWTP with minimum cost, minimum area footprint and minimum carbon footprint which meets the effluent quality discharge regulation (COD, BOD and TSS).

2. Problem statement

The problem definition in this work is as follows: Wastewater feed f ϵ F is treated by a series of treatment stages beginning from preliminary treatment p ϵ P, chemical treatment r ϵ R, biological treatment s ϵ S, and tertiary treatment t ϵ T to produce treated wastewater as shown in Figure 1. In chemical treatment and biological treatment, a certain amount of sludge will be generated. These generated sludges will flow into the sludge treatment process u ϵ U. Based on the problem shown in Figure 1, a mathematical model is formulated.

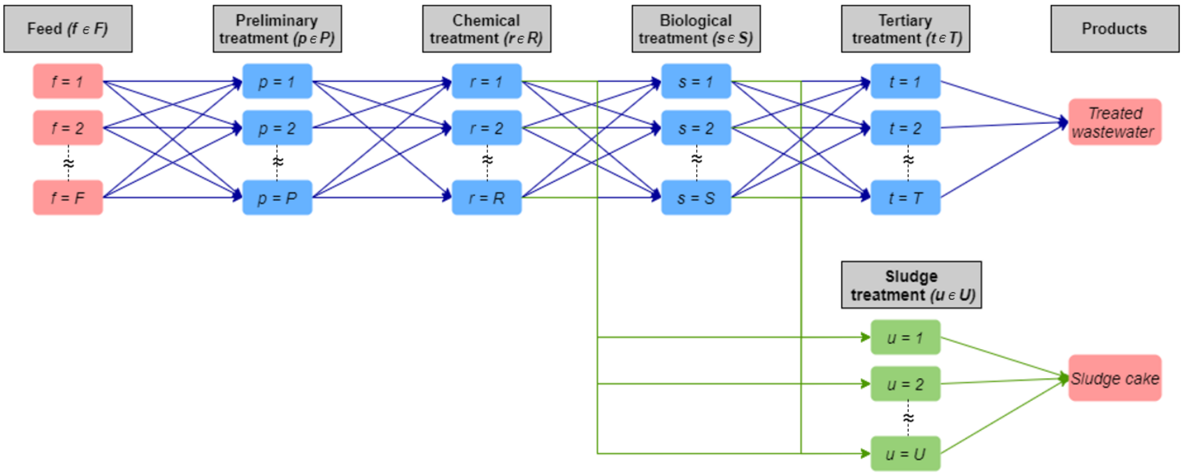

Figure 1: Generic superstructure of WWTP

3. Fuzzy multi-objective optimisation (FMOO) model

The mathematical model developed in this work consists of flowrate balance, component balance, area footprint, cost computation, carbon footprint, and fuzzy equations as shown in each subsection. Based on Figure 1, these equations will be repetitive at each treatment stage. A more generic formulation is presented in this paper where index *a* represents the previous treatment stage, index *b* represents the present treatment stage and index *c* would represent the subsequent treatment stage. For instance, to formulate equations for biological treatment *s*, the present index *b* represents chemical treatment *s* (*b* = *s*). Index *a* will represent the preceding chemical treatment *r* (*a* = *r*) and index *c* will represent the succeeding tertiary treatment *t* or sludge treatment *u* (*c* = *t*,*u*).

3.1 Flowrate and component balance

This work aims to synthesise an organic WWTP considering COD balance, BOD balance, and TSS balance. In this respect, the formulation for volumetric flowrate balance and component balance for an organic WWTP can be found in Ho et al. (2019). The concentration of components (COD, BOD and TSS) present in the treated wastewater from the synthesised WWTP will always comply with the local discharge regulation as shown in the constraint in Eq(1).

$$C^{component,treated\ WWT} \leq C^{\text{component,std}} \quad (1)$$

3.2 Area footprint

The formulation of area footprint is based on the area factor, P (m^2) obtained from literature review or industrial vendors as shown in Eq(2). $Area_b$ represents the area footprint for present treatment stage *b* while P_b^{Area} represents the area factor for each technology in the present treatment stage *b*.

$$Area_b = P_b^{\text{Area}} \qquad \forall b \qquad (2)$$

3.3 Cost computation

The total investment cost for technology *b*, $Cost_b^{\text{Total}}$ (USD/m^3) includes the capital expenditure (CAPEX), operating cost, and the land area cost formulated as shown in Eq(3) to Eq(6). The CAPEX for present technology *b*, $Cost_b^{\text{CAPEX}}$ (USD) is formulated based on the CAPEX factor, P_b^{CAPEX} (USD) retrieved from literature reviews or industrial vendors. The operating cost for present technology *b*, $Cost_b^{\text{Opt}}$ (USD/m^3) is contributed from the material cost for technology *b*, $Cost_b^{\text{Mat}}$ (USD/m^3) and power cost for technology *b*, $Cost_b^{\text{Power}}$ (USD/m^3). In addition, $Cost_b^{\text{Area}}$ (USD) represents the total land area cost for present technology *b* and P_b^{LandCost} (USD/m^2) represents the area cost factor for technology *b*. To annualised the CAPEX and land area cost, an annualised factor, P^{Annual} is obtained based on the expected operating years and inflation rate.

$$Cost_b^{\text{CAPEX}} = P_b^{\text{CAPEX}} \qquad \forall b \qquad (3)$$

$$Cost_b^{\text{Opt}} = \text{Cost}_b^{\text{Mat}} + \text{Cost}_b^{\text{Power}} \qquad \forall b \qquad (4)$$

$$Cost_b^{\text{Area}} = Area_b P_b^{\text{LandCost}} \qquad \forall b \qquad (5)$$

$$Cost_b^{\text{Total}} = (Cost_b^{\text{CAPEX}} + Cost_b^{\text{Area}})P^{\text{Annual}} + Cost_b^{\text{Opt}} \qquad \forall b \qquad (6)$$

3.4 Carbon footprint

Carbon footprint formulation is presented in Eq(7) where, $Carbon_b$ (kg CO_2/d) is the carbon footprint for present technology *b*, E_b^{power} (kWh/m^3) is the power consumption for technology *b* and P_b^{carbon} (kg CO_2/kWh) is the carbon footprint factor representing how much carbon dioxide will be released for every power consumption.

$$Carbon_b = F_b^{\text{in}} E_b^{\text{power}} P_b^{\text{carbon}} \qquad \forall b \qquad (7)$$

3.5 Fuzzy optimisation

To incorporate multiple objectives that are contradictory in nature, fuzzy optimisation is used as shown in Eq(8) to Eq(10). Fuzzy optimisation integrates multiple objectives into a single parameter called the degree of satisfaction, λ. λ ranges from 0 to 1, whereby 0 indicates the total area footprint, cost, and carbon footprint are approaching their upper limits (undesirable) while 1 indicates these optimisation objectives are approaching their lower limits (desirable). Higher λ represents higher satisfaction for each objective. The total area footprint, cost, and carbon footprint are represented by *TotArea* (m^2), *TotCost* (USD/m^3) and *TotCarbon* (kg CO_2). Superscript UL represents the predetermined upper limit each objective while superscript LL represents the predetermined lower limit for each objective. These predetermined limits can be obtained based on decision-makers' interests or determined by optimising the model one objective at a time (Zadeh, 1965).

$$\frac{\text{TotArea}^{\text{UL}} - TotArea}{\text{TotArea}^{\text{UL}} - \text{TotArea}^{\text{LL}}} \geq \lambda \qquad (8)$$

$$\frac{\text{TotCost}^{\text{UL}} - TotCost}{\text{TotCost}^{\text{UL}} - \text{TotCost}^{\text{LL}}} \geq \lambda \qquad (9)$$

$$\frac{\text{TotCarbon}^{\text{UL}} - TotCarbon}{\text{TotCarbon}^{\text{UL}} - \text{TotCarbon}^{\text{LL}}} \geq \lambda \qquad (10)$$

To solve the fuzzy model, the fuzzy degree of satisfaction, λ will be maximised as shown in Eq(11).

$$\text{Maximise } \lambda \qquad (11)$$

4. Case study

In this case study, a WWTP is synthesised to treat sago wastewater obtained from a sago-based biorefinery in Sarawak, Malaysia (Wan and Ng, 2015). Sago wastewater enters at a flowrate of 276 m^3/d with a COD level of 7,763 ppm, BOD level of 3,362 ppm, and TSS level of 4,942 ppm. Based on the local discharge legalisation (Standard B), the synthesised WWTP in this work will reduce the level of COD, BOD and TSS present in the sago wastewater to 200 ppm, 50 ppm, and 100 ppm (Department of Environment Malaysia, 2010). A series of wastewater treatment technologies suitable for this case study were included as shown in Figure 2.

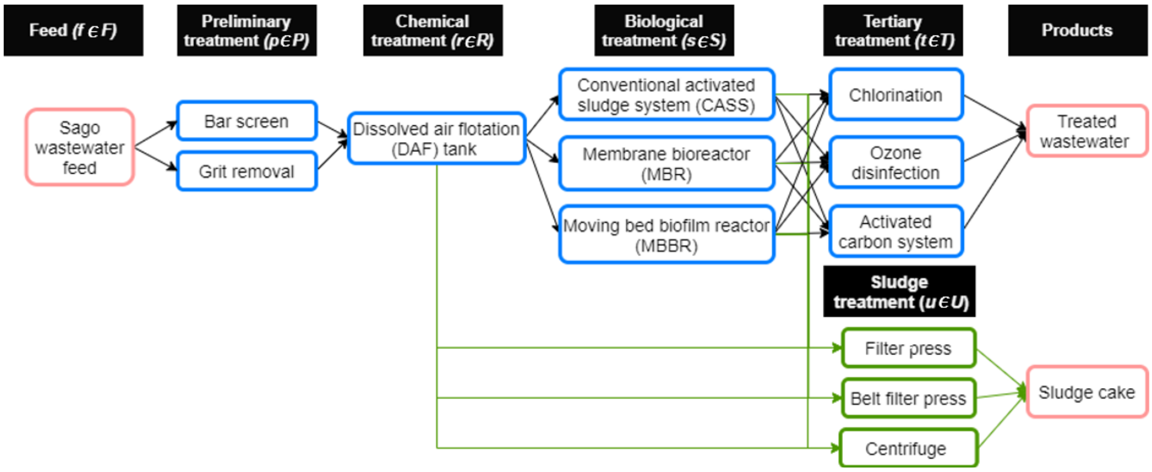

Figure 2: Case study superstructure of sago biorefinery WWTP in Sarawak, Malaysia.

Table 1 and Table 2 summarised the wastewater treatment technologies specifications such as removal efficiency, dryness, CAPEX, material cost (MAT), power cost (POW), area footprint (AF), and power consumption (E) obtained from industrial partners. To calculate the power cost, local electricity rates were obtained. According to Sarawak Energy Berhad (2020), the electrical rate is USD 4.58/kWh for heavy industry class I1. In addition, the carbon emission factor for Malaysia is 0.693 kg CO_2/kWh (International Energy Agency (IEA), 2016). The land area cost of the WWTP is calculated based on local industrial land rates in Sarawak which is USD 212.25/m^2 (Malaysian Investment Development Authority (MIDA), 2020).

Table 1: Specifications of case study wastewater treatment technologies (Lakghomi et al., 2015)

Technologies	Removal efficiency (%)			CAPEX (USD)	MAT (USD/m^3)	POW (USD/m^3)	AF (m^2)	E (kWh/m^3)
	TSS	COD	BOD					
Bar Screen	65	0	0	4,128	0	0	15.00	0
Grit Removal	40	0	0	7,523	0	0	20.00	0
DAF	91	70	65	3,440	0.34	1.02	15.95	0.222
CAAS	85	85	88	22,936	0.60	12.17	-	2.652
MBR	99	90	90	68,807	0.46	16.35	-	3.565
MBBR	85	90	92	57,339	0.37	9.27	-	2.022
Chlorination	16	56	55	18,349	0.73	0.12	7.84	0.026
Ozone disinfection	60	83	70	22,936	0.46	4.82	3.92	1.051
Activated carbon system	58	65	60	11,009	1.15	0.50	6.09	1.110

Table 2: Specifications of case study sludge treatment technologies (Wang et al., 2019)

Technologies	Dryness (kg SS/m^3)	CAPEX (USD)	Operating cost (USD/m^3)		Area (m^2)	E (kWh/m^3)
			MAT	POW		
Filter press	25.0	18,349	0.11	8.26	2.80	1.800
Grit Removal	29.9	22,936	0.11	6.78	4.30	1.478
Activated carbon system	28.5	27,523	0.13	11.47	3.00	2.500

The FMOO model developed for this case study is a mixed integer non-linear programming (MINLP) model. Using a commercial optimisation software, LINGO (version 18.0) the case study is solved with computer specification of Intel ® Core ™ i7-6500U @ 8 GB RAM, x64-based processor. An optimum wastewater treatment pathway with minimal area footprint, total investment cost, and carbon footprint will be synthesised. This will be done by optimising each objective individually to determine the upper and lower limits for each optimisation objective as summarised in Table 3.

Table 3: Summarised results for each optimised objective WWTP pathways.

Pathways	Preliminary treatment	Chemical treatment	Biological treatment	Tertiary treatment	Sludge treatment
Min. area footprint (Pathway A)	Bar screen	DAF	MBBR	Ozone disinfection	Centrifugal
Min. total investment cost (Pathway B)	Bar screen	DAF	MBBR	Ozone disinfection	Filter press
Min. carbon footprint (Pathway C)	Grit removal	DAF	MBBR	Activated carbon system	Belt filter press

The area footprint, total investment cost, and carbon footprint for each optimised pathway were tabulated in Table 4. By optimising each objective individually, the best (lower limit) values and worst (upper limit) values can be identified to set a range for trade-offs. A global optimised wastewater treatment pathway at a degree of satisfaction, λ of 0.5813 is synthesised as shown in Figure 3. The optimum wastewater treatment process consists of bar screen, dissolved air flotation (DAF) tank, moving bed biofilm reactor (MBBR), activated carbon system, and filter press. Comparing to the worst scenarios, by applying a maximum trade-off percentage of 58.13 %, the area footprint is decreased from 60.10 m^2 (Pathway C) to 54.75 m^2. At the same time, the cost needed for the WWTP is decreased from 20,273.43 USD/d (Pathway B) to 19,286.77 USD/d where lesser advanced technology in preliminary treatment and sludge treatment is chosen. In addition, a significant amount of carbon footprint is reduced from 657 kg CO_2/d (Pathway A) to 549 kg CO_2/d.

Table 4: Comparison of wastewater treatment pathways at different optimisation objectives.

Objective function	Area footprint (m^2)	Total investment cost (USD/d)	Carbon footprint (kg/d)
Min. area footprint (Pathway A)	52.33^{LL}	19,915.93	657.38^{UL}
Min. total investment cost (Pathway B)	53.13	18,576.11^{LL}	631.75
Min. carbon footprint (Pathway C)	60.10^{UL}	20,273.43^{UL}	472.04^{LL}
Final optimised results (λ=0.5813)	54.75	19,286.77	549.64

*^{UL} – Upper limit ^{LL} – Lower limit

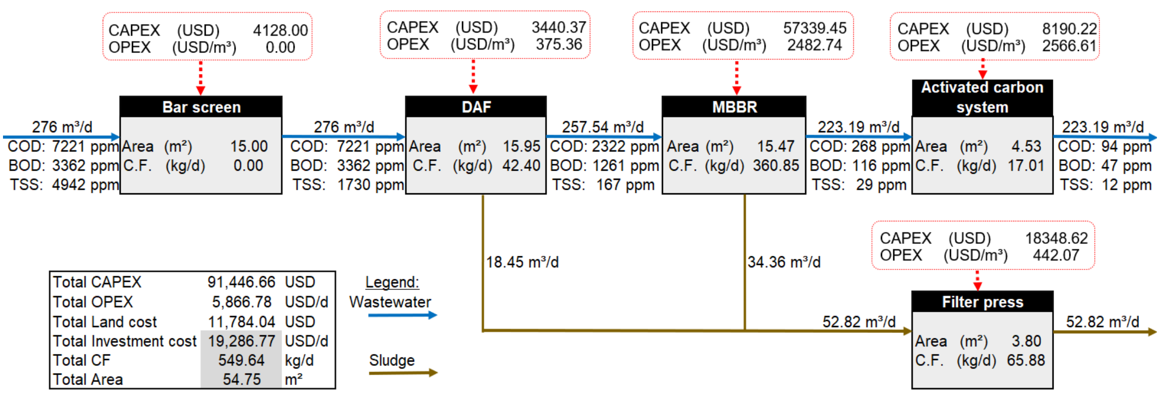

Figure 3: Optimal configuration of case study WWTP with traded off cost, area footprint, and carbon footprint.

5. Conclusion

In conclusion, this work had developed a decision-making tool to synthesise WWTP based on different optimisation objectives such as minimum cost, minimum area footprint, and minimum carbon footprint. The contradicting problem between these optimisation objectives is solved via FMOO. The case study in this work had demonstrated that area footprint is an important criterion to be considered during the synthesis of WWTP as the cost associated with the land area is significant. Results from the case study indicate that a maximum trade-off at approximately 58 % would reduce 5.35 m^2 of area footprint, 986 USD/d of total investment cost, and 108 kg CO_2/d of carbon footprint. For future work, the weightage of each optimisation objective can be included in the model to allow a more extensive decision making during a WWTP synthesis.

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References

Ang M.S., Duyag J., Tee K.C., Sy C.L., 2019, A multi-period and multi-criterion optimization model integrating multiple input configurations, reuse, and disposal options for a wastewater treatment facility, Journal of Cleaner Production, 231, 1437–1449.

Adeni D.S., Abd-Aziz S., Bujang K., Hassan M.A., 2010, Bioconversion of sago residue into value added products. African Journal of Biotechnology, 9(14), 2061–2021.

Butler R.A., 2013, Malaysia has the world's highest deforestation rate, reveals Google forest map, Mongabay News & Inspiration from Nature's Frontline <news.mongabay.com/wildtech/2013/11/malaysia-has-the-worlds-highest-deforestation-rate-reveals-google-forest-map/> accessed 06.06.2020.

Cai W., Liu J., Zhang X., Jern W., Liu Y., 2016, Generation of dissolved organic matter and byproducts from activated sludge during contact with sodium hypochlorite and its implications to on-line chemical cleaning in MBR, Water Research, 104, 44–52.

Department of Environment Malaysia, 2010, Environmental Requirements: A guide for investors, Putrajaya, Malaysia.

Drews A., 2010, Membrane fouling in membrane bioreactors — Characterisation , contradictions , cause and cures, Journal of Membrane Science, 363, 1–28.

Fernandez-Dacosta C., Posada J.A., Ramirez A., 2016, Techno-economic and carbon footprint assessment of methyl crotonate and methyl acrylate production from wastewater-based polyhydroxybutyrate (PHB), Journal of Cleaner Production, 137, 942–952.

Ho J.Y., Wan Y.K., Andiappan V., Ng D.K.S., 2019, Material flow cost account-based approach for synthesis and optimisation of wastewater treatment plant, Chemical Engineering Transactions, 76, 529–534.

International Energy Agency (IEA), 2016, Carbon dioxide emission factor <www.iea.org/> accessed 06.06.2020.

Lakghomi B., Lawryshyn Y., Hofmann R., 2015, A model of particle removal in a dissolved air flotation tank: Importance of stratified flow and bubble size, Water Research, 68, 262–272.

Malaysian Investment Development Authority, 2020, Cost of Industrial Land, Starting a Business <www.mida.gov.my/home/starting-a-business/posts/> accessed 06.06.2020.

Padrón-páez J.I., Almaraz S.D., Román-martínez A., 2020, Sustainable wastewater treatment plants design through multiobjective optimization, Computers and Chemical Engineering, 140, 1–16.

Pan W., Yu L., Wang S., Wang X., 2014, A fuzzy multi-objective model for provider selection in data communication services with different QoS levels, International Journal of Production Economics, 147, 689–696.

Sarawak Energy Berhad., 2020, Tariff Category Units <www.sarawakenergy.com/> accessed 06.06.2020.

Wan Y.K., Ng D.K.S., 2015, Synthesis and Optimisation of Total Water Network via Material Flow Cost Accounting (MFCA)-Based Approach, Chemical Engineering Transactions, 45, 1519–1524.

Wang H., Xu G., Qiu Z., Zhou Y., Liu Y., 2019, Chemosphere NOB suppression in pilot-scale mainstream nitritation-denitritation system coupled with MBR for municipal wastewater treatment, Chemosphere, 216, 633–639.

World Wide Fund Nature (WWF), 2020, Forests <www.wwf.org.my/about_wwf/what_we_do/forests_main/> accessed 27.05.2020.

Yunus N., Jahim J., Anuar N., 2014, Batch fermentative hydrogen production utilising sago (Metroxylon sp.) starch processing effluent by enriched sago sludge consortia, International Journal of Hydrogen Energy, 39(35), 19937–19946.

Zadeh L.A., 1965, Fuzzy Sets, Information and Control, 8, 338–353.

Zimmermann H.J., 1978, Fuzzy programming and linear programming with several objective functions, Fuzzy Sets and System, 1(1), 45–55.