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A Systematic Fuzzy-based Framework for Synthesis and Optimization of an Eco-Industrial Park (EIP) for Oil Palm Industry

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Cultivation of oil palm are commonly held in rural, which had caused the sustainability of rural areas become increasingly important and challenging due to the growth of challenges in environment and economical aspects in the industry. The development of sustainability in rural areas are very limited while environmental sustainability becomes one of the important issues within the process engineering industry, where reuse, recycle and recover the wastewater and nutrient are always being encouraged. To address this issue, the concept of Eco-Industrial Park (EIP) could be adopted where resources allocation and exchange could be done among the involved parties to ensure sufficient utilities and resources are fulfilled in the rural areas and then further promote environmental and economic sustainability. To ensure EIP is feasible, optimum resources allocation and exchange should be pre-determined to know the expected minimum profit of parties involved before any decisions made on the development of EIP in rural area while maintaining minimum carbon dioxide emission for environmental sustainability. A systematic framework is required to guide decision makers in solving this complicated problem. There are limited research works focused on the development of a systematic framework for the synthesis of an oil palm industry based EIP that involving nutrient recovery from the wastewater treatment. This leads to the objective of this work to develop a systematic framework to synthesize an oil palm industry based EIP considering the nutrient recovered from wastewater treatment. This framework also served as a guidance in determining the optimum resources allocation and exchange based on decision-making factors (e.g., deserved profit and carbon dioxide emission) for each of the possible combinations of the cooperating parties using fuzzy optimization approach. An oil palm based EIP case study has been solved to demonstrate the proposed framework. The results show the combination of water and wastewater treatment plant with power generation plant is the best combination in profit earning while maintaining reasonable carbon dioxide emission.

1. Introduction

Rural areas and agriculture sector play an important role in economic development of a country. Agricultural activity in rural areas had largely produced food or non-food raw materials, which are widely used in different industries (Rashid et al., 2019). Express expansion of agricultural activity had led Southeast Asia dominant agriculture based economic in the international trade (Shevade and Loboda, 2019). Development of industrial plantation such as oil palm and rubber tree plantation had caused large amount of wastewater generated within the area. Most of the plantations are located at rural areas, where it is not well developed and wastewater generated in rural areas are not well allocated and treated. Since agriculture development is significantly increased, the nutrient demand is also increased accordingly. Nutrient is important in agriculture sector to ensure the harvesting rate and quality of the agriculture products (Vrignon-Brenas et al., 2019). Challenges such as difficulties in transporting nutrients are arising when sustainable nutrient supply is in highly demand.

Faragò et al. (2021) suggested that valuable resources in rural areas such as nutrients could be recovered from wastewater. This is because the wastewater containing high amount of nutrients such as nitrogen and phosphorus, which is valuable in agriculture. With proper technology implementation, the recovered treated water then can be further utilised for domestic or plantation usage in rural area, whereby the recovered nutrients

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could be further allocated. The limitations such as limited infrastructure development or sustainable resources applying had affected the sustainability of rural areas. Limited infrastructure development such as roads and stable power supply may affect the consistency of production rate in rural areas, which will directly affect the revenue generated of the factories or plantations involved. These limitations had caused the rural area needs to be more self-sustaining. To address this problem, the concept of eco-industrial park (EIP) could be adopted. EIP can be known as a business community where the businesses parties involved in the community are enhancing environmental and economic performance by collaborating with each other (Halonen and Seppänen, 2019). Throughout the collaboration, resources exchanging such as water, energy and materials could be conducted within parties. By exchanging the available resources within EIP, concept of industrial symbiosis could be promoted where the benefits for parties involved is higher than the party standing alone. The concept of EIP is to produce a more environmentally friendly product, while it is cost effective and efficient in waste management.

EIP promotes multi-stages benefit where it can enhances the perspectives of sustainability, environment and economy (Halonen and Seppänen, 2019). Waste generated within EIP will be reduced significantly due to higher efficiency of utilising available resources, where exchanging of resources between parties in EIP will allow the parties involved to reduce the production cost (Perrucci et al., 2022). This shows EIP could bring many positive impacts to sustainable enhancement. One thing is there are limited works to demonstrate how an optimum oil palm industry based EIP that involving nutrient recovery from wastewater treatment could be developed in a systematic way. Optimum resources allocation and exchange among the potential parties of EIP should be pre-determined based on different optimization objective (e.g., maximize profit, minimize carbon emission, etc.) prior to EIP forming. This is important to prevent any forming of EIP that is not achieving the minimum expectation (i.e., minimum profit). Each potential party should have their minimum expectation before they decided to join as an EIP member. There could be multiple parties and objectives involved in EIP. This could leads to different solution. To identify the optimum solution for EIP, the concept of fuzzy optimization could be adopted.

Fuzzy optimization is commonly applied in situations where the decision-making factors are conflicting with each other and leading decision cannot be made due to unable to process the uncertain information (Sarwar et al., 2023). Aviso et al. (2010) applied fuzzy optimization model in water exchanging of EIP, where wastewater optimization was conducted in this case. Aviso et al. (2010) used fuzzy optimization model in water integration and hydrogen recovery as case study where it was studied that constrained network in EIP can be satisfied. Fuzzy optimization model was also used in determining the requirement for waste treatment and energy recovery. The optimal method was also determined by maximizing the energy production with minimal payback period (Sadegh et al., 2015). Tay et al. (2022) applied Fuzzy Optimization Model to determine the suitable technology to minimize the carbon emission by combined heat and power (CHP). Fatimah et al. (2021) also applied Fuzzy Optimization Model to determine allocation of wastewater segregation before centralized wastewater treatment. The current applications of fuzzy optimization are mainly focused in determining the suitable technologies for a single party application in EIP but not identifying the beneficial parties to be collaborated with in the EIP. In this work, the concept of fuzzy optimization will be adopted to identify the potential parties instead of technologies for the optimum EIP configuration. There are also limited research works focused on the development of a systematic framework for the synthesis of oil palm industry based eco-industrial park that involving nutrient recovery from wastewater treatment using fuzzy optimization. This leads the research objective of this work to develop a systematic framework to synthesize an oil palm industry based EIP considering the nutrient recovered from wastewater treatment using the concept of fuzzy optimization.

2. Methodology

A systematic framework has been developed as shown in Figure 1. The parties involved in oil palm EIP are first identified to list out all the possible combinations of party. For example, if 3 parties (A, B, C) are involving in the EIP, all the possible combinations for these three parties needed to be listed out. Then, decision-making factor(s) can be determined based on the involved parties' desired such as cost savings, profit earnings, carbon emissions, etc. Relevant data such as production yield, single unit price and energy consumption are required to collect. A case study superstructure needs to be developed based on the possible pathways of party collaboration. This is to allow generic equations to be formulated according to the decision-making factors such as mass balance, volumetric flowrate, contaminant, and profit equations. Eq(1) shown the general mass balance equation, where the mass input of a party is always equal to mass output.

$$\sum M^{\mathrm{IN}} = \sum M^{\mathrm{OUT}} \tag{1}$$

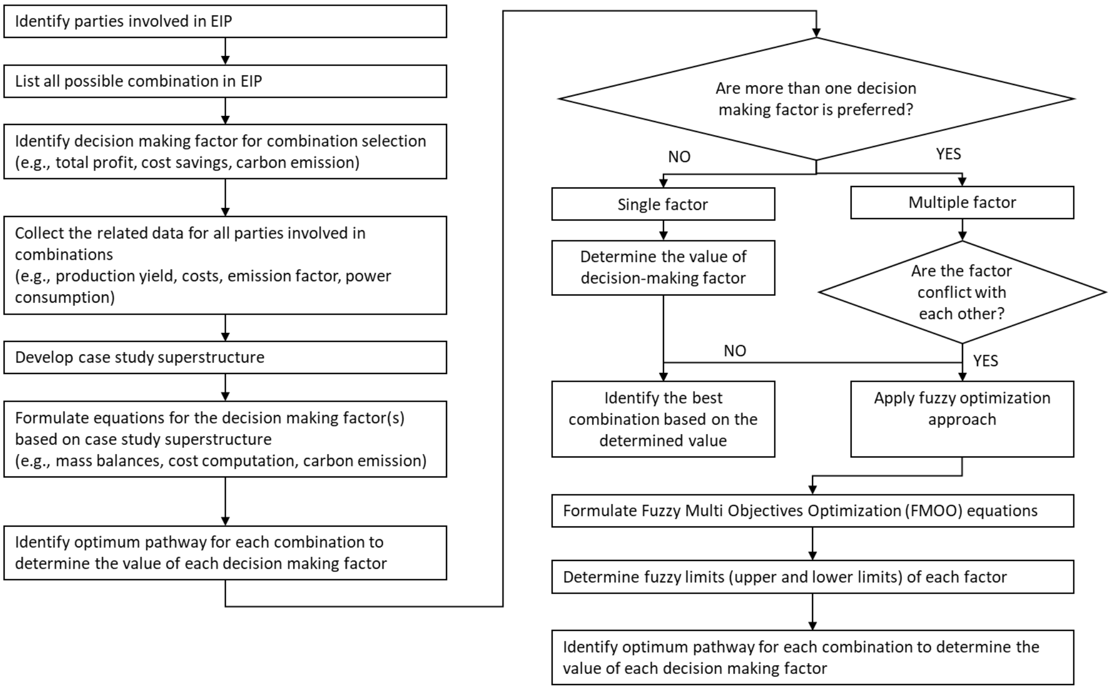

Figure 1: Framework to determine optimum combinations of EIP

This generic volumetric flowrate can be expressed as the following equation, where *F* is identified as volumetric flowrate and $F_{j,k}^{\text{descp}}$ is to annotate the flowrate of specific material (notated as 'descp' in the formula) from one party to another party, for example from Party *j* to Party *k*.

$$F^{\text{descp}} = \sum F_{j,k}^{\text{descp}} \tag{2}$$

Relevant equation can be further generated based on volumetric flowrate, such as production yield, carbon emission, etc. Eq(3) showed the generic formulation of carbon emission. C_j^{TOTAL} is known as the total carbon emission of Party *j*, while E_j^{power} is the energy consumption of party *j* in kWh/day and $\mathrm{CE}^{\text{biogas}}$ is the carbon emissions rate of biogas based power generation plant while $\mathrm{CE}^{\text{grid}}$ is the carbon emissions rate of fossil fuel based power generation plant. Both $\mathrm{CE}^{\text{biogas}}$ and $\mathrm{CE}^{\text{grid}}$ are in unit of kg CO_2/ kWh.

$$C_j^{\text{TOTAL}} = \left(E_j^{\text{power}} * CE^{biogas}\right) + \left(E_j^{\text{power}} * CE^{grid}\right) \tag{3}$$

To ensure the sustainability of a party, profit calculation is also very important in the study. Eq(4) shows the generic total profit calculation where it is considering of profit gained by providing the services and also the expenses of the party. F_j^{PRODUCT} is the flowrate of selling products of Party *j*, where $M^{profit\,1}$ is the market price of the products. F_j^{expenses} is the flowrate of expenses, where it can be utility or raw materials and $M^{expenses\,1}$ is the market price to be charged.

$$P_j = \left(F_j^{\text{PRODUCT}} * M^{profit\,1}\right) - \left(F_j^{\text{expenses}} * M^{expenses\,1}\right) \qquad \forall j \tag{4}$$

If the study is conducted with single factor, the values of equations can be used directly to determine the optimum combination of EIP. However, if it is the case of multiple decision-making factors, conflicts between factors have to identify. For example, if profit earning increased when carbon emission increased, it is then considered as conflicting factors where fuzzy optimization equation, Eq(5) is needed. Obj is a value that ranges between Obj^L and Obj^U .Obj^L is notated as the lower boundary and $Obj^U$is the higher boundary of the resulted value.

$$\frac{Obj - Obj^L}{Obj^U - Obj^L} = \lambda \tag{5}$$

The value of λ is then maximized as shown in Eq(6). It can be explained that if λ approached to be 1, the target decision making factors will be approaching to the maximisation objective, while λ as 0 is approaching to the minimisation objective.

$$Max = \lambda \tag{6}$$

3. Case Study

The parties involved in the EIP is firstly determined, where all possible combination of EIP will be listed out. In this case, palm oil plantation and palm oil mill are grouped as Party A, where the supply of oil palm fruit will be directed from plantation. Water and wastewater treatment plant are classified as Party B where wastewater treatment plant is responsible to treat the wastewater from Parties A and C to produce partially treated water that is suitable for irrigation within EIP. Water treatment plant produces high quality water such as process water and tap water to ensure sufficient water utility within EIP. The treated water will be recycled to water and wastewater treatment plant to maintain their operation and the recovered nutrients will be recycled to wastewater treatment to cultivate bacteria to maintain biological treatment performance. Biogas based power generation plant is known as Party C in the EIP, where the electricity within EIP is supplied by the plant. The possible combinations are {A}, {B}, {C}, {A,B}, {A,C} and {A,B,C}. The possible resources allocation and exchange is identified based on the parties involved which then case study superstructure shown in Figure 2 is generated. In this case, profit earning and carbon emission had been identified as the decision-making factors to fulfil the research objectives. The relevant data for every party such as unit operation cost, production yield, emission factor, nutrient, water and power consumption, etc. are collected from literature review and industry partner.

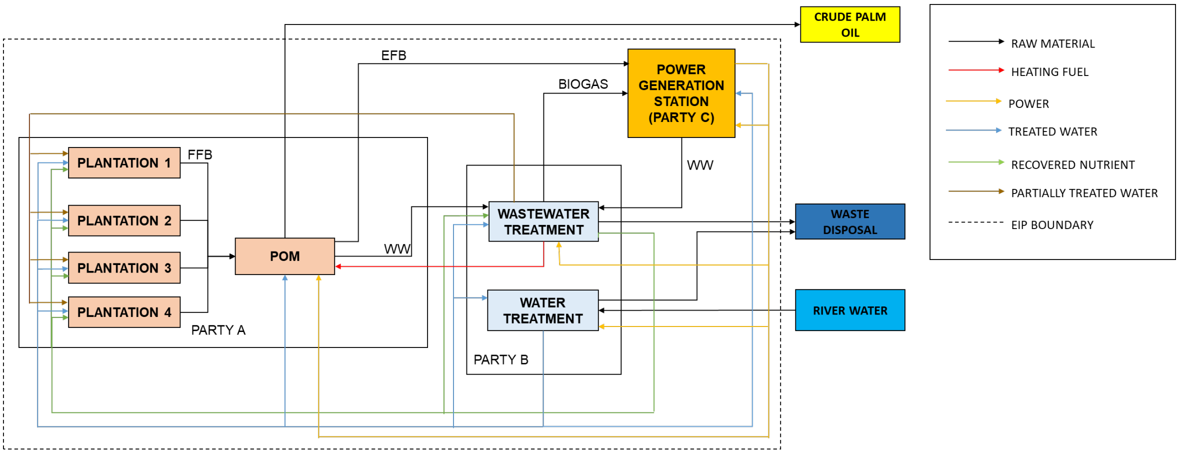

Figure 2: Case study superstructure

4. Results and discussion

The optimization results of decision making factors are calculated via a commercial mathematical software LINGO V20.0 in computer with Intel i7-10th Gen processor. Table 1 summarised all the results of optimization.

Table 1: Optimization results based on different objectives

Optimization Objectives	Minimize Carbon Emission		Maximize Profit		Maximize λ
Coalition	Profit (USD/d)	Carbon Emission (kg CO2/d)	Profit (USD/d)	Carbon Emission (kg CO2/d)	λ
{A}	87,370.33	994.99	88,238.47	996.87	0.514
{B}	79,795.96	645.62	80,031.61	650.69	0.666
{C}	-3,961.71	392.61	3,992.90	441.16	N/A
{A,B}	273,458.90	939.72	282,102.80	1,024.74	0.679
{A,C}	115,773.90	1,250.89	139,225.10	1,380.88	0.180
{B,C}	63,352.90	998.79	73,382.40	1,383.85	0.756
{A,B,C}	88.592.03	1945.67	92,030.86	2,265.97	0.593

To determine the total profit earning of combination of EIP, summation of total profit from each party has been done and similar steps are conducted to determine the total carbon emission of the combinations. The total profit then has been maximised while the carbon emission of combinations has then been minimised. Due to the conflict between both optimization objectives fuzzy optimization is adopted by maximizing λ.

4.1 Maximization of Profit Earning

From Table 1, it was studied that combination of {A,B} resulted in highest profit earning, which involves of plantation and palm oil mill as Party A, wastewater treatment and water treatment plant as Party B. The product of Party A will be crude palm oil, empty fruit bunch and wastewater. The crude palm oil will be sold to the market, while empty fruit bunch (EFB) will be sold to third party to generate incomes. Since palm oil mill will generate large amounts of palm oil mill effluent (POME), the POME generated will be sent to Party B for treatment. It is worthy to mention that Party B play an important role in EIP to ensure all the wastewater being treated before discharged into nearby waterways. Party B could be the government itself, not only to make profit but also making sure all the wastewater will be treated and complied with regulations without any secret dumping from industries.

The wastewater collected by Party B will be converted to partially treated water, biogas, recovered nutrients and sludge. The partially treated water is then supplied to oil palm plantations for watering purposes. The recovered nutrients also used in oil palm plantations. This caused the usage of raw chemical nutrients can be reduced in EIP. Water treatment plant is set to supply the water demand among EIP's parties, where river water is pumped to the water treatment plant for treatment. In this scenario, it was assumed zero charges to fulfil the water demand of Party A since Party A is one of the parties of the optimum EIP as shown in Figure 3. Based on the Table 1, the results show the coalition of {A,B,C} has lower profit compared to {A,B}. This is due to Party A able to generate more profit by selling off the palm oil and biomass in {A,B} while Party B can make profit from selling the biogas to third party. If Party C is taking part in {A,B,C} they need to exchange the resources such as biomass, biogas and electricity. This explains why the profit earned is lower in {A,B,C}. It is worthy to note that this result is just for Malaysia's case. Different countries' case could lead to different results since the unit cost of resources are different from one country to another country.

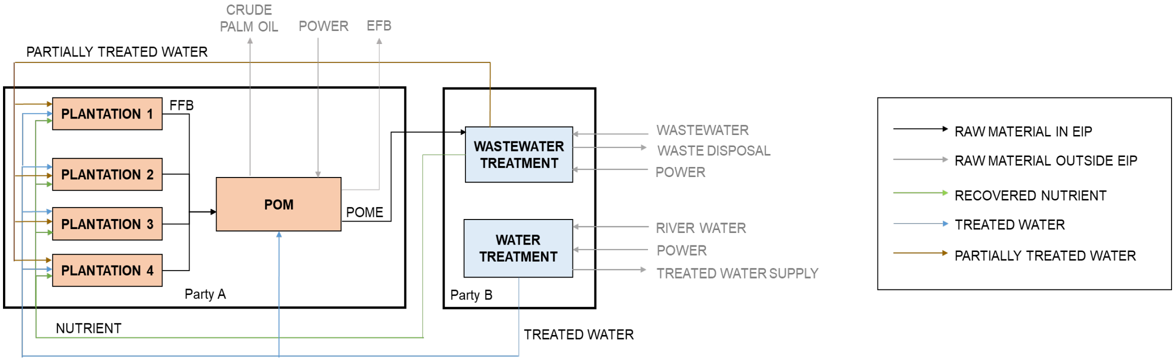

Figure 3: Optimum EIP for the case of maximisation of profit.

4.2 Minimization of Carbon Emission

If the single decision making factor is to minimize carbon emissions, Party C which is the power generation plant stand alone will emit the least carbon dioxide, due to the adaptation of biogas as raw materials. It was studied that the profit earning is negative, which can be saying that it is infeasible for power generation plant to stand alone in EIP as negative profit will not sustain the party in EIP. The second best option is Party B stands alone which will results the least carbon emission.

4.3 Fuzzy Optimization

By studying the values of profit and carbon emission, conflict occurs where the higher the profit earning, the higher the carbon emission of combination in EIP. Therefore, fuzzy optimization model is introduced, where λ is used as the decisive variable to determine the optimum EIP combination. The coalition of {C} have been excluded from the optimization model due to its negative profit earning as shown in Table 1. The value of λ is also summarized in Table 1.

From Table 1, it was studied that the combination of {B,C} resulted in the highest value of λ, which can be understood as the optimum combination for EIP resources exchange and allocation. This is because Party B able to fulfil the biogas and water demand of party C, while Party C able to provide the energy to Party A and ensure the sustainability. The simplified superstructure for this case is shown as Figure 4.

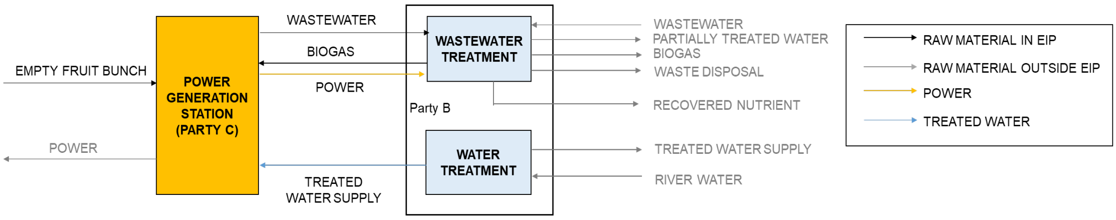

Figure 4: Optimum EIP for the case with fuzzy optimization.

5. Conclusions

A systematic framework to synthesize an oil palm industry based EIP considering the nutrient recovered from wastewater treatment using the concept of fuzzy optimization was developed successfully. This framework provides guidance in identifying the optimum oil palm industry based EIP with optimum combination of resources allocation and exchange based on decision-making factors (i.e., carbon emission and profit). The developed framework has been demonstrated using a Malaysia case study with involving palm oil plantation and mill, water and wastewater treatment plant, and biogas power generation plant. In this case study, combination of palm oil plantation and mill, and water and wastewater treatment plant resulted in highest profit earning while water and wastewater treatment plant stands alone resulted in lowest carbon emissions. It was also studied that results are conflicted between these the two decision-making factors. Fuzzy Optimization model was introduced, where combination of water and wastewater treatment and power generation plant shows the highest λ value, which is the optimum combination based on the multiple decision-making factors, maximizing profit and minimizing carbon emission.

References

Aviso K.B., Tan R.R., Culaba A.B., Foo D.C.Y., Hallale N., 2010, Fuzzy optimization of topologically constrained eco-industrial resource conservation networks with incomplete information, Taylor & Francis, 43(3), 257–279.

Sarwar M., Ali G., Chaudhry N.R., 2023, Decision-making model for failure modes and effect analysis based on rough fuzzy integrated clouds, Applied Soft Computing, 136, 110148.

Faragò M., Damgaard A., Madsen J.A., Andersen J.K., Thornberg D., Andersen M.H., Rygarrd M., 2021, From wastewater treatment to water resource recovery: Environmental and economic impacts of full-scale implementation, Water Research, 204, 117554.

Sa'ad S.F., Wan Alwi S.R., Lim J.S., Abdul Manan Z., 2021, Centralized Water Reuse Exchange in Eco-Industrial Park Considering Wastewater Segregation, Chemical Engineering Transactions, 83, 1–6.

Halonen N., Seppänen M., 2019, Eco-Industrial Parks, Chapter In: W Leal Filho, A Azul, L Brandli, P Özuyar, T Wall (Ed.), Responsible Consumption and Production, Springer, Cham, 1–13.

Perrucci D.V., Aktas C.B., Sorentino J., Akanbi H., Curabba J., 2022, A review of international eco-industrial parks for implementation success in the United States, City and Environment Interactions, 16. 100086.

Rashid M.F., Ngah I., Misnan S.H., 2019, Revitalizing Rural Areas in Malaysia: A Framework for Economic Revitalization, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 385(1), 012004.

Taskhiri M.S., Behera S., Tan R.R., Park H.S., 2014, Fuzzy optimization of a waste-to-energy network system in an eco-industrial park, Journal of Material Cycles and Waste Management, 17, 476–489.

Shevade V.S., Loboda T.V., 2019, Oil palm plantations in Peninsular Malaysia: Determinants and constraints on expansion, PLoS ONE, 14(2), e0210628.

Tay Z.X., Lim J.S., Wan Alwi S.R., Manan Z.A., 2022, Optimization of Cogeneration Energy System in an Industrial Park using Cooperative Game Theory, Chemical Engineering Transactions, 94, 913–918.

Vrignon-Brenas S., Gay F., Ricard S., Snoeck D., Perron T., Mareschal L., Laclau J.P., Gohet E., Malagoli P., 2019, Nutrient management of immature rubber plantations. A review, Agronomy for Sustainable Development, 39(11), 1–21.