Conceptual Design of a Process Plant for the Production of Natural Dye from Merbau (*Intsia bijuga*) Bark

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**Abstract.** The damage to the aquatic life, cancer health effect on humans, and low water quality are the effects caused by the use of synthetic dyes in the textile industry. For this reason, it is necessary to reduce the use of synthetic dyes. By producing the natural dye, people can overcome this problem, and provide a business strategy to improve the country's economic growth. One of the natural dye substances is tannin, which can be produced from various types of wood bark. Indonesia provides an abundant source of wood and bark waste. One source is Merbau wood from Sinar Wijaya Plywood Industry which is located in Dawai-Serui, Yapen Waropen Regency, Papua Province, and PT Wijaya Sentosa, Teluk Wondama Regency, West Papua Province. Other kind of source is mangrove bark from Bintuni Utama Murni Wood Industry. The other type is mahogany bark from Wonosobo Regency, Central Java. For example, in this paper the technology review is focused on Merbau bark and sawdust, as waste obtained from PT Wijaya Sentosa (PT WS). Based on the research conducted previously, aqueous extraction is known as the most effective method to extract tannin from its biomass source. Because it is waste from the wood industry, the sustainability of the raw material is assured, and we can produce a continuous tannin plant. This paper presents the conceptual design of a process plant for the production of natural dye from Merbau (*Intsia bijuga*) bark. The process plant consists of a bark size reduction, extraction, evaporation, and drying machines. The design analysis of constituent machines and their performance evaluations were carried out using appropriate design equations. The designed process plant was simulated to ensure its functionality. The results of its performance were analysed and the cost of products was estimated.

**Keywords:** conceptual design, process plant, intsia bijuga, tannin, natural dye.

1. **Introduction**

Over 700,000 tons of textile dye is produced annually around the world (Chequer *et al.*, 2013). This large number brought great news for our textile global market, on the other hand have a tremendous environmental impact. Textile dye contributes a major part in water body pollution (Lavanya *et al.*, 2014). Due to the inefficient process design, about 10-50% of the textile dye is released to the environment. About 200,000 tons of textile dye is released to the environment annually, from three...
main activities of a dyeing process: preparation, dyeing, and finishing. The severe environmental damage as an impact from synthetic textile dye usage is a serious and important problem to society. The serious illness to the human health, negative health impact to the animal, and damage to the aquatic ecosystem (Samchetshabam, Hussan, and Choudhury, 2017) are the trouble caused by the usage of natural dye which produces some hazardous chemicals such as amines group (Fröse et al., 2018). More over, the synthetic textile dye usage which produces a lot of waste is difficult to degrade naturally. Unlike the synthetic one, natural dyes are easy to degrade in the environment, so it has a relatively small impact on the environment.

Many kinds of plant that is available in Indonesia can produce a natural dye. One of the available sources in Indonesia is the Merbau tree, it can be found in the tropical forest in lowlands, sometimes in the seashore. Total production is 265,923 m³ and Papua province is the largest producer of Merbau tree woods among other provinces, the productivity is 36.81 trees/Ha (Malik et al., 2005). It produced 0.25 million m³ of Merbau wood in 2015. For the past six years, the Merbau tree production tends to decrease annually. This tree height reached 50 meters tall, with a maximum trunk diameter is 2.5 meters. Merbau is a hardwood plant and its trunk can be used for construction material, furniture, and also wooden floor. Also, every part of the tree is very useful for many purposes. Leaves and bark, which are as production waste, contain valuable substances. This valuable substance is extracted from Merbau wood, mainly known as polysaccharides such as tannins. This tannin can be used for various purposes (Suseno et al., 2013).

Several studies prove that tannin can be extracted using various methods. The solvent extraction of tannin from mangrove bark using ethanol and aqueous extraction has proven scientifically in laboratory scale. It has a high yield and a simple purification method (Warnoto, 2015). Other research has studied the effect of the solvent to wood bark ratio towards tannin recovery (Sasas et al., 2000). Tannin production from mangrove bark also has been studied for heavy metal adsorbent material usage. The effect of temperature and time to extraction process also studied by a previous researcher (Kartikaningsih, B and Danarto, 2011). Tannin has successfully been extracted using water, alcohol, and hydro alcoholic substance (Danarto, Prihananto, and Pamungkas, 2011). Methanol as a solvent also able to extract tannin from Merbau bark with a percent recovery of 29% (Malik et al., 2016). Extraction of tannin using microwave-assisted extraction produced high yield and purity (Cahyani and Novidayasa, 2016).

The previously explored method can fulfill the basic requirement of the chemical production process on a larger scale. To enter the industrialization scenario, the method must pass through several hierarchies, namely: engineering design, design requirements, feasibility studies, and conceptualization. The fourth stage that is conceptualization also known as concept design holds an important role before the idea of this plant construction can be realized into a physical plant. It is a step-by-step and iterative method to turns this idea into reality. These steps are known as the hierarchy of decision, starting from batch versus continuous, input-output structure, recycle, separation system, and heat integration. The conceptual design production plant of plantain flour has been studied by another researcher (Ayodeji, 2016). The idea is to create a flour production plant by considering the quality and quantity of the flour and the process efficiency. The plant utilized renewable resources that are plantain fruit. The process is a series of operations, start from washing, slicing, drying, milling, and sieving. Transporting equipment also provided to make the system more autonomous without human intervention. The plant is built within the steel frame to make the size smaller, compact but slim. The difference between past studies and this study is the plant size and also product usage. While this research is focused on the food product, this study focused on a textile product. Hence, the presence of impurities in the product can be tolerated. This work focuses on the whole process plant from three
process units. The research paper has a similar goal, to provide the optimum design from various options. Past research is provided as a basis for this study.

This paper presents the conceptual design of a process plant of natural dye from Merbau bark and sawdust waste. The purpose of this study also studied thoroughly the optimum design of process plant of natural dye from the waste, so it solves the problem in term of efficient raw material usage, process time, and energy integration.

2. Design Concept
The raw materials used in this plant are bark and wood sawdust of Merbau, as a waste of PT WS. Both have a moisture content of 18%, tannin content 3.6% from sawdust and 29% from wood bark, and density of 835 kg / m3. As a solvent, water will be used at room temperature. Production capacity can be estimated by obtaining the waste production rate data from PT WS. The maximum capacity of Merbau woods in PT WS is 148,077 m3/year. From the company data, 70% of the wood production number goes to the product and the rest of it becomes a waste. From our calculation, we have 30,416 tons/year of Merbau waste, with 88% of it as wood bark and 12% as sawdust.

A process plant in this study consists of a preparation unit, extraction unit, and purification unit as shown in Figure 1. The preparation unit consists of raw material storage, wood chipper, and a hammer mill. The extraction unit consists of a mixer-settler and filtration. The purification unit consists of a belt press filter, evaporator, steam ejector, spray dryer, and cyclone separator. The three units have transporting equipment, the solid transporting equipment using conveyor and the fluid is transported using pipe and pump.

The powder of tannin will be stored temporarily in a hopper feeder before it is ready to be packaged. Tannin which is packaged in woven bags has a purity of 95% (mass fraction), has a solid phase in powder form and has 100 mesh undersize.

![Figure 1. Flow Diagram Process of Natural Dye Plant](image.jpg)

2.1. Design Consideration
Design of natural dye from Merbau waste process plant must follow these considerations:
  a. Efficient usage of raw material
  b. Optimal process time
  c. Heat energy integration
To meet the design requirement, the framework provided by Douglas’ Hierarchy of Conceptual Design must be followed.

2.2. Material Selection of Equipment
One of the important aspects of concept design is material selection. Proper material selection can avoid operability problems or hazardous conditions. It also helps in choosing the equipment at a reasonable price. Below are the consideration of selecting the best material for designing, according: a.
Physical and mechanical properties, b. Reliability, c. Availability, d. Maintainability, e. Chemical properties, f. Aesthetic characteristic, and g. Cost-effectiveness (Avallone and Iii, 1996).

### Table 1. Material Selection of Equipment

| Plant Equipment          | Material Used                  | Justification                                                                 |
|--------------------------|--------------------------------|-------------------------------------------------------------------------------|
| Raw material storage     | Cement, clay brick, and clay roof | A cheap material, but has an excellent strength to protect weather influence and wind force |
| Wood chipper             | Galvanized mild steel          | Does not contaminate, shearing resistance, have rigidity                      |
| Hammer mill              | Galvanized mild steel          | Does not contaminate, shearing resistance, have rigidity, adequate toughness |
| Belt conveyor            | Rubber                        | Low cost, resistant to corrosion                                              |
| Flight Conveyor          | Carbon steel                   | Light metal, low cost, easy to transport, does not contaminate                |
| Hopper-Feeder            | Galvanized mild steel          | Rigidity, does not contaminate, have a decent strength                        |
| Mixer                    | Galvanized mild steel          | Does not contaminate, corrosion resistance, adequate hardness, and isolates heat loss |
| Settler                  | Galvanized mild steel          | Does not contaminate, corrosion resistance, high durability                   |
| Centrifugal pump         | Carbon steel                   | Corrosion resistance                                                          |
| Belt press filter         | Anti-corrosion Q235 carbon steel | Cheap, durable, anti-corrosion                                                |
| Steam ejector            | Carbon Steel SA grade D        | Anti-corrosion, thermal resistance, high durability                           |
| Evaporator               | Carbon Steel SA grade D        | Anti-corrosion, thermal resistance, high toughness                           |
| Spray dryer              | Carbon Steel SA grade D        | Anti-corrosion, thermal resistance, high toughness                           |
| Cyclone separator        | Galvanized mild steel          | Excellent toughness, cheap, light material                                   |
| Blower                   | Carbon Steel SA grade D        | Corrosion resistance                                                          |

3. Design Analysis

The next part consists of a technology review from each unit operation. The technology review contains a brief description of various types of technology that suitable to perform the process. The selection is performed based on some considerations, which are capital and operational cost, holding time, and efficiency.

3.1. Primary reduction machine

Selection of primary reduction machine is depending on raw material properties itself. The obtained wood bark 3-20 cm width, 1-3 cm thick, and 2-4 meters long. It has high hardness but also very brittle. It has natural fiber. To shrink up the wood bark into a smaller size (10-30 mm), the operation needs to be performed by cutting process. There are two options of cutting machines: the disc chipper and the drum chipper. Disc chipper can produce a fine wood bark and has a relatively high cutting capacity, but the drum chipper is 8% more effective in terms of fines production rate per energy input. The drum chipper also able to produce smaller fines with more uniform size. Therefore, the drum chipper is selected as the cutting machine.

### Table 2. Selection of Wood Chipper

| Aspect                     | Disc chipper                  | Drum chipper                  |
|----------------------------|-------------------------------|-------------------------------|
| Energy along the blade     | Not uniform (as a function of radius) | Uniform                      |
3.2. Secondary reduction machine

After the wood chips have been produced, it undergoes another size-reduction step which is important to maintain size uniformity of all particles entered the extractor. Various options were available to perform this secondary crushing step. They are rod/ball mills, hammer mills, and cage mills. The selection is based on feed specifications. Due to its high fiber content and smaller size, a hammer mill is selected among other choices because it meets the feed condition demand. Biomass resource is best processed using cutting principle rather than crushing. Hammer mills provide cutting edge screening for better product size and maintain uniformity, providing this as a great choice for the secondary cutting process.

| Table 3. Wood Mills Selection |
|-----------------------------|
| Aspect                      | Hammer Mills | Ball Mills | Rod mills |
| Feed size, mm               | 5-30         | 1-10       | 5-20      |
| Capacity, ton/hr            | 0.1-5        | 10-300     | 20-500    |
| Reduction ratio             | 400          | 100        | 10        |
| Power input, kW             | 1-100        | 1-10       | 5-20      |
| Operational cost, USD/hour  | 86.4         | 96.6       | 100.7     |
| Capital cost, $             | 800,600      | 1,118,900  | 1,246,200 |
| Reference(s)                | (Naimi et al., 2006) | (Couper et al., 2005) | (Couper et al., 2005) |

3.3. Extraction

3.3.1. Process Selection

A various extractions process has been studied previously. These extraction processes have different characteristics and also disadvantages. Depends on its raw material, a natural dye can be produced through several routes of synthesis. In Table 1 below, the current method for extracting tannins is presented (Mansour, 2018). The process may be combined by ultrasonic and microwave-assisted extraction, but to narrow down our choices the process is eliminated due to its complexity in a large scale.

| Table 4. The Comparison between Extraction Method |
|-----------------|
| Method          | Yield, % | Materials needed     | Material cost, $/kg | Reference(s)              |
| Solvent extraction | 4.47-16.47% | Aqueous or organic solvents | 0-3.1 | (Wina, Rakhmani and Tangendjaja, 2010) |
| Alkali/Acid     | 5-51%   | A dilute acid/alkali | 0.2-0.4 | (Seabra et al., 2018) |
| Fermentation    | 2-4%    | Water and alkali | 0 | (Cuong et al., 2019) |
3.3.2. Solvent selection

It has been studied by other work that tannin is soluble in water and organic solvent with certain solubility (Malik et al., 2016). An available and cheap organic solvent known as ethanol. It is volatile and able to dissolve tannin at ambient temperature. The water, however, can dissolve tannin better than ethanol at a higher temperature. With this consideration, we intend to compare which solvent is suitable for tannin extraction. Literature provided to serve these material properties (Yaws, 1999). One of the disadvantages of using water is high evaporation energy. These disadvantages can be eliminated by using a triple-effect evaporator. Those three advantages are enough to make water as a feasible choice rather than ethanol. To make the justification of the solvent selection much clear, a simple calculation was provided to determine the raw profit of the extraction. Raw profit can be calculated by subtracting the product cost with a solvent cost. The formulas provided as follows:

$$R_p = P_c - S_c$$  \hspace{1cm} (1)

where $R_p$ is Raw Profit, $P_c$ is product cost, and $S_c$ is solvent cost.

| Aspect                  | Ethanol | Water | Notes                                                                                                                                 |
|-------------------------|---------|-------|---------------------------------------------------------------------------------------------------------------------------------------|
| Normal Boiling Point, °C| 78.37   | 100   | Lower temperature is preferred to prevent tannin degradation at 120 °C. The lower the evaporation energy, the lower the evaporator cost. |
| Evaporation Energy, kJ/kg | 841     | 2257  | Low hazard solvent also prevent the consequences such as massive release or explosion.                                                 |
| Flash Point, °C         | 14      | Non-Flammable |                                                                                                                                 |
| Material Cost, $        | 2.44    | 0     | The price must be reasonable with tannin extracted                                                                                   |

When using ethanol as a solvent, it has a solvent-to-feed ratio for 4:1 (Danarto, Prihananto and Pamungkas, 2011). With this, the total annual ethanol cost is estimated at $731.20. Natural colorant recovery from ethanol extraction is 21% and total annual sales are $9,510.24. While using water as a solvent has a solvent-to-wood ratio of 3:1 (Malik, et.al., 2016). Regardless of its usage, water is low cost to obtain. Additionally, the pumping cost must be counted. Percent recovery of water extraction is 22.5%. The total product cost is $10,189.54. Raw profit of ethanol extraction is $8,779 and it is lower than water extraction that is $9,770.15. Based on this calculation, water solvent is chosen as extraction method.

3.3.3. Stage determination and dimension calculation

The effect of a number of the stage towards percent recovery has been studied. The calculation was using the stage-by-stage calculation method through many trial and error. The recovery increase as the number of stage increase. The increase in recovery did not goes significantly between 4th and 5th stage. Hence, four stages are sufficient to get the desired extraction product.

The determination of a mixer-settler dimension must follow the capital and operational expenditure consideration. The mixer-settler configuration has met the optimum size and design requirement. The percent recovery is a function of the number of stages, and the number of stages will affect the capital cost and operational cost. Below provided the study of Total annual cost (TAC) between stage number.
\[ TAC = \frac{FC}{3} + OC \]  

where TAC is Total Annual Cost, FC is fixed cost, and OC is Operational Cost.

### 3.4. Sludge Filter

The sludge obtained from extraction activity must be separated using a solid-liquid separator, apply the centrifugation or filtration. The most effective method is filtration because it has high solid content. There are many types of Filtration equipment, i.e. press filter and rotary filter. The solid content is higher than water, it doesn’t need stirring. The selection of filter based on: simplicity, operability (washing), and economy. Based on the three parameters, the belt press filter is the suitable equipment for separating the wood residue and water.

#### Table 7. Filter Selection

| Aspect             | Rotary filter | Press filter | Centrifuge       |
|--------------------|---------------|--------------|------------------|
| Investment cost, US$ | 32578         | 2807         | 167335           |
| Process type       | Medium filtering | Slow filtering | Medium and slow filtering |
| Rate of cake buildup | 0.1-10 cm/min | 0.1-10 cm/hr | 0.1 cm/hour – 10 cm/min |
| Reference(s)       | (Couper et al., 2005) | (Couper et al., 2005) | (Couper et al., 2005) |

### 3.5. Evaporator

#### Table 8. Evaporator Selection

| Aspect                  | Falling film evaporator | Natural circulation evaporator | Forced circulation evaporator |
|-------------------------|-------------------------|--------------------------------|--------------------------------|
| Heat transfer coefficient, W/(m²K) | 500-1000                | 300-900                         | 900-3000                       |
| Retention time, s       | 5-10                    | 16                              | 41.6                           |
| Investment cost, $/m²   | 33168                   | 18151                           | 172755.8                       |
| Notes                   | Low susceptibility of fouling | Higher pressure drop | High fouling and scaling resistance |
| Reference(s)            | (Sinnott, 1983)         | (Sinnott, 1983)                | (Sinnott, 1983)                |

The selection of evaporator depends on the feed characteristics. It is known that the feed is temperature-sensitive and can be broken by continuous heating surpassing the 120 °C. Additionally, the feed is in slurry form and very prone to fouling issues. Based on feed characteristics, it is known that the slurry retention time must be short. Available choices are falling film evaporator, circulation evaporator, and rising film evaporator. From its retention time, it is known that falling film evaporator is the optimum choice among the other.

### 3.6. Dryers
Evaporated slurry has 30% of water content. This water fraction must be decreased further, to meet the product specification in powdered form. Continuous dryer is selected, they are pneumatic dryer, fluidized bed dryer, drum driers, rotary dryer, rotating shelf, and dispersion dryer. Dispersion (spray dryer) is chosen rather than other dryers because it has high drying capacity, short drying time, uniformity of product, and simple equipment:

A further calculation is performed and the result can be shown below:

| Table 9. Dryer Selection |
|--------------------------|
| Aspect                   | Pneumatic Dryer | Fluidized bed dryer | Spray Dryers |
| Capacity, kg/hour        | 12246.9940     | 50802.3454          | 103         |
| Drying time, s           | N/A            | 27                 | 8.3         |
| Final moisture           | 0              | 0.2                | 4           |
| Cost, $                  | 9197           | 2200               | 231313      |
| Heat consumption, Btu/lb water evaporated | 1600 | 2200 | 8018,649 |
| Fan Power, HP            | 110            | 70                 | 1           |
| References               | (Couper et al., 2005) | (Couper et al., 2005) | (Couper et al., 2005) |

3.7. Solid-Gas Separator

The outlet air from the drying machine still has solid content. To remove this solid content, equipment for performing solid-gas separation must be provided. Some options available for this operation are bag filter, cyclonic separator, dust chamber, and electrostatic precipitator. The selection is based on retention time, separator efficiency, and investment and operational cost. Hence, a cyclonic separator is chosen because it fulfils those selection criteria.

| Table 10. Solid-Gas Separator Selection |
|----------------------------------------|
| Aspect                                | Bag filter | Cyclonic separator | Electrostatic precipitator |
| Pressure drop                         | 11-13 inch water | 157 Pa | 0.5 inch water |
| Separator efficiency                  | 99.8       | 99.8 | >99%          |
| Capital cost, $                       | 412,315    | 310  | 1,180,000     |
| Operational cost, $/year              | 371,000    | 15   | 424,000       |
| Specified size, ft²                   | 10.661     | L= 1.2 m | 15850 |
| D=0.1180 m                            | (Couper et al., 2005) | (Bashir, 2015) | (Couper et al., 2005) |
| Reference(s)                          | (Turner et al., 1987) | (Turner et al., 1988) |

3.8. Solid Transporting Equipment

Solid transporting equipment selection based on the solid characteristics which are free-flowing, low density, and small size material. The equipment must protect the product and raw material from the wind force and carryover problem. It should be closed conveying equipment. Available equipment for horizontal use is pneumatic conveyor, screw conveyor, and belt conveyor. Based on operability and effectiveness, it is proper to choose closed type belt conveyor as solid transporting equipment for horizontal usage. Vertical usage available is bucket elevator, flight conveyor, and pneumatic conveyor. Hence, the flight conveyor is chosen from the power required, simplicity, and investment cost.

3.9. Fluid Transporting Equipment

The pump selection is based on feed material properties, required power, and capital cost. Several choices are available such as a centrifugal pump and reciprocating. The selection is based on the head provided by the system and using a chart provided by (Sinnott, 1983). The head can be calculated by using a basic energy equation (Brown, 1950).
The obtained head for this pump varies, depend on the location. The range head for the pump is around 7.1–7.3 m and the flowrate is around 8.07 m³/hour. Specific speed (Ns) obtained value is above 400 rpm. Therefore, the obtained number can conclude the suitable pump that is a centrifugal pump.

3.10. Power requirement
Table 11 shows the summary of the power requirement of the natural dye process plant

| Equipments       | Power Demand, hp | Equipments       | Power Demand, hp |
|------------------|------------------|------------------|------------------|
| Storage fan      | 25               | Flight Conveyor  | 10               |
| Pump             | 65               | Wood chipper     | 100              |
| Belt Conveyor    | 23               | Hammer Mill      | 430              |
| Stirrer          | 240              | Blower           | 4                |
| Belt press       | 7                | Spray dryer      | 590              |
|                  |                  | Total power needed | 1494           |

4. Conclusion
The design of the overall process has been selected based on various options. The solvent extraction is a chosen process because it is cheap and simple and has expected yield of 4.47-16.47%. The water solvent is chosen because it has theoretical profit as much as $9,770.15, with raw material input of 3937.9878 kg/hour. For cutting equipment selection, the drum chipper followed by hammer mills is the best possible selection for size reduction. With its 8% higher efficiency, the drum chipper is the best option and the cost of hammer mills is cheaper. Falling film evaporator, and spray dryer is the best water reduction equipment because it has the shortest retention time with a reasonable price. Cyclone separator is the cheapest solid-gas separator even it is not possible to reach 100% efficiency. The plant power demand is 1494 HP. Further steps are detailed design and feasibility study.

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