Conceptual Design of Fertilizer Applicator for Oil Palm on Terrace Cultivation

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Abstract. The mechanical application of fertilizer for oil palm planted on terraces is still constrained by the narrow path which is difficult to pass by a power spreader. The objective of this research was to develop a conceptual design of fertilizer applicator for oil palm planted on terraces. The design requirements were developed based on a) terrace and track conditions, b) fertilizers and fertilization conditions, c) available prime movers, and d) user needs. Five design concepts were obtained: 1) an applicator with left and right arms to distribute the fertilizer, 2) an all-terrain vehicle equipped with a manually operated fertilizer injector, 3) an applicator equipped with a hole digger, 4) an applicator equipped with a shovel, and 5) an applicator equipped with a rotary tiller. The concepts were evaluated and compared with the current power spreader. The evaluation results showed that the applicator equipped with a rotary tiller had the most advantages on the expected criteria. The final design concept uses a 110 cm wide mini crawler tractor as the prime mover and is equipped with a hopper and a spinner disk for metering and conveying the fertilizer, and a 20 cm wide rotary tiller in the front of the machine.

1. Introduction
Fertilization work is one of the most important activities in the cultivation of oil palm crops [1]. However, the rapid development of oil palm plantations in Indonesia raises one of the problems of labor constraints for oil palm cultivation activities, especially for fertilizer application. Therefore, large oil palm plantations applied mechanization on the fertilizer application. Fertilization is mechanically carried out mostly on flat palm plantations, using a mechanical fertilizer spreader operated by a four-wheeled tractor [or attached to a small crawler tractor [2-4]. The power spreader operates on the track between the rows of oil palms and spreads the granular fertilizer onto the soil surface near the row of oil palm trees. Mechanized fertilizer application may result in more efficient nutrient use and labor savings.

Some of the oil palm plantations are wavy, sloping and hilly. In sloping areas, the oil palms are planted following contour lines with terracing system. The sloping land is formed terraced and the oil palms are planted along the path of the terraces. Terraces must be installed on sloping land to provide adequate access for field workers and harvesters and to reduce soil erosion and surface run-off. The width of the terrace depends on the steepness of the land and ranges from 2-3 m. On the terrace, oil palms are planted somewhat closer to the side of the cliff terrace. In the palm oil terracing system, fertilization is still done by manual, and cannot be done mechanically.

There are problems faced in providing fertilizer for oil palm planted on the slopes, namely: 1) difficult to be crossed by a power spreader for mechanical fertilization, 2) manually fertilization is less...
effective and cannot be guaranteed the application rate, 3) fertilization by sowing above the soil surface at risk of rainwater runoff, so fertilization efficiency is low. It is very important to apply the fertilizers in the best manner over the areas of the estate that are likely to result in the most efficient uptake of nutrients, and to minimize negative environmental impacts related to over-fertilization, land degradation, and pollution from heavy metals such as cobalt and eutrophication by P application [1].

In such conditions, fertilization needs to be done more effectively, with the help of an appropriate machine. Current equipment and machinery cannot be used in the area. Therefore it is necessary to develop or design a fertilizer application machine for oil palm planted in slope area. For the purpose, some conceptual design should be developed and evaluated. Conceptual design is the key to achieve innovation, for it is at this stage when product concepts are assessed and selected before they are developed into final products sold in the market [6].

The objective of this research was to develop a conceptual design of fertilizer applicator for oil palm planted on terraces.

2. Materials and methods

2.1. Research activities
For developing the oil palm fertilizer applicator, the following activities have been conducted.
1. Identification of fertilizer characteristics and fertilization system used (in the plantation)
2. Measurement of land and soil conditions on terraces of sloping plantation.
3. Review of tractors available on site and can be used to drive the fertilizer applicator.
4. Identification of machine specifications.
5. Development and evaluation of fertilizer machine design concepts.
6. Design analysis.
7. Engineering drawing and 3D modeling.

The study was conducted in two oil palm plantations owned by Astra Agro Lestari Company located in Riau Province. The intensity of application of fertilizers and application rate of oil palm fertilization conducted by the company was recorded and documented in accordance with the conditions in the field. Sample of fertilizer used by the company was taken and its characteristics are measured, including: water content, bulk density, angle of repose, and grain size distribution.

Physical and mechanical properties of the soil on the terraces were measured, including soil texture, water content, soil bulk density, penetration resistance, and shear resistance. Penetration resistance was measured around the palm, at 0.75-1.5 m from the palm, using a penetrometer with the cone size of 2 cm². The measurement was conducted at 0-20 cm depth. The shear resistance of the soil was measured using a penetrometer equipped with a shear ring. The measurement was conducted at the soil surface and a depth of 10 cm. In addition, there were also measurements of the slope of the land, the width of the available track on the terrace, and the length of the planting rows.

Available tractors on site that can be used to drive the fertilizer applicator were identified and studied. Then, discussion with the plantation manager and the technical staffs was conducted to identify the user needs in developing the design specifications.

2.2. Overview of the oil palm planting conditions on the sloping land
There are mainly three conditions of oil palm cultivation on the sloping land found in the field. The first, the oil palms are planted on the sloping land as shown in figure 1(a). Secondly, the sloping land that has been planted with oil palm is made of terraces so that there is a machine-passable track (for fruit evacuation or a crawler type tractor) as shown in figure 1(b). In this condition, the palm is located at the upper terrace about 0.5-1 m above the passable terrace. The third is the sloped land which is terraced and then planted with oil palm on the terrace as shown in figure 1(c). In the last condition, palms are located on the same terrace with a track for fruit evacuation as wide as 1-1.5 m which can be traversed on the contour slope. The track condition is relatively flat and the slope is up to 10°.
The soil condition around the oil palm tree (palm circle) was quite dense. The rooting area was at a depth of 10 to 40 cm. The soil density conditions around the oil palm are shown in table 1. These conditions were quite dense and could be easily crossed by crawler-type vehicles or large tractor wheels. The bulk density of the soil ranges from 0.85 - 1.22 g/cm$^3$. The average bulk density of the soil around the palm was 1.16 g/cm$^3$, whereas in the track the average bulk density was 0.94 g/cm$^3$. The deeper, the soil becomes lighter, especially after passing through the dense layer of oil palm root zone. The shear strength of the soil around the palm is higher, compared to that of the track.

Table 1. Soil penetration resistance around the area of 0.75-1.5 m from the palm and on the track.

| Depth (cm) | Penetration resistance (kPa) |
|-----------|-----------------------------|
|           | Near the palm | On the track |
| 0-5       | 10.2           | 4.6          |
| 5-10      | 14.7           | 6.4          |
| 10-15     | 20.6           | 6.8          |
| 15-20     | 24.2           | 6.8          |

2.3. Overview of fertilizer and fertilization system

Most plantations were fertilized with NPK fertilizer (and other fertilizers), which were spread manually, and spread using a power spreader. Based on the survey results in the oil palm plantation and discussion with the plantation manager, the condition of fertilization and fertilization system that are recently implemented are as follows.

1. The fertilizer (NPK, urea, etc.) are sowing on the ground, near the oil palm trees.
2. Application rate of fertilizer according to the needs of plants, in the range of 2-3 kg NPK per palm.
3. In the flat area, fertilization was done mechanically using a power spreader attached to a crawler tractor or a four-wheeled tractor (figure 2).
4. Field working performance of the mechanical fertilization was 4 ha/h (using a crawler type tractor (Canycom)); or 5 - 8 ha/hour (using a four-wheeled tractor).
5. The machine operating costs was in the range of IDR 11,500- IDR 15,500 per ha.
6. The fertilizer characteristics are shown in table 2.

Table 2. Physical characteristics of NPK fertilizer used.

| Bulk density | Water content (db) | Angle of repose | Granules size |
|--------------|-------------------|-----------------|---------------|
| 1.2 g/cm$^3$ | 7.05 %            | 40°             | 1.4 mm        |
|              |                   |                 | maximum 3.3 mm|
|              |                   |                 | minimum 0.7 mm|
Figure 2. (a) Fertilizer application using a power spreader attached on a crawler type tractor “Canycom”, (b) a fertilizer spreader attached to a four-wheeled tractor.

2.4. Design Specification and Criteria
On the occasion of this research, oil palm fertilizer applicator that will be developed is for the cultivation of oil palm planted in the contour line of sloping land, with a narrow track. From the discussion with the company technical team, and taking into account the conditions of the land and oil palm plantations to be applied, and by including the results of the discussion with the user, the machine to be developed has the characteristics as listed in table 3.

Table 3. Characteristics of fertilizer applicator developed and the design criteria

| No. | Component/conditions       | Characteristics                                                                 |
|-----|----------------------------|-------------------------------------------------------------------------------|
| 1   | Fertilizer placement      | Fertilization beneath the soil with a depth of 10-15 cm, in the root zone     |
|     |                             | (according to the condition of the plant) at a certain distance from the oil   |
|     |                             | palm tree. Placement of fertilizer in the disconnected furrow.                 |
| 2   | Fertilizer loading and     | • Able to load the required fertilizer (on the fertilizer hopper) the required |
|     | refilling                  |     amount (minimum for two-row crops, for refilling on one side only).        |
|     |                             | • Types of granular fertilizers commonly used on site                          |
| 3   | Machine operation          | • Operated across the pathways of oil palm planting terrace, which was         |
|     |                             |     provided and can be safely passed by a four-wheeled tractor or mini crawler|
|     |                             |     tractor.                                                                   |
|     |                             | • Implementation of fertilizer applicator is not a separate unit that is pulled |
|     |                             |     (trailing)                                                                 |
| 4   | Main construction          | A fertilizer hopper; a metering system; a spinner and fertilizer distributors; |
|     |                             |     power transmission systems, frames and supporting parts                    |
| 5   | Prime mover (tractor)      | • A four-wheel tractor or small crawler tractor available at the site, or can   |
|     |                             |     be provided by the company.                                               |
|     |                             | • The tractor has a three-point linkage or hydraulic system for lifting and     |
|     |                             |     lowering the fertilizer applicator unit.                                  |

2.5. Design concept selection method
The design requirements were developed from the results of analysis based on a) terrace and track conditions, b) fertilizers and fertilization conditions, c) available prime movers, and d) user needs. Then
design concepts were developed by considering the design requirements. The design concepts were then evaluated, and the best concept was selected. Evaluation criteria were extracted from stakeholder requirements. The key requirements then were identified through prioritization as primary, secondary and tertiary.

The evaluation of the design concepts was conducted using the following evaluation procedure:

**Step 1. Screening**

**Step 2. Comparison**

**Step 3. Decision-making.**

The purpose of screening was to eliminate any concepts that were not feasible or acceptable. Screening involved comparing concepts to a series of absolute criteria [5]. The following two questions were used for screening concepts:

**Question 1.** Is the concept currently feasible? Alternative questions: Will it work? Will it require additional technological research and development? Unless strong evidence suggested that a concept was not feasible, then proceeded to **Question 2.**

**Question 2.** Will the concept meet each of the customer requirements? Unless strong evidence suggested that a concept will not meet one or more customer or design requirements, the concept was saved for Step 2 and continued screening other concepts. After screening every concept, then proceeded to Step 2.

The purpose of comparison was to evaluate the relative advantages and disadvantages of each concept. For evaluating the relative advantages and disadvantages of each concept, the Pugh method was used. The first seven steps for using Pugh’s method during concept selection were:

1. Choose the criteria by which the concepts will be evaluated.
2. Formulate the decision matrix.
3. Clarify the design concepts.
4. Choose the initial datum concept.
5. Run the matrix. During this step, each concept was compared with the datum for each criterion.
6. Evaluate the ratings.
7. Establish a new datum and rerun the matrix.

The power spreader that was recently used by the company was used as the datum concept, in the selection process. The purpose of decision-making was to choose the concept(s) to develop further. When one design concept was clearly superior to the rest, the decision-making step was straightforward in choosing the superior concept. If the first comparison step resulted more than one better concepts with the same score, then the remaining concepts were evaluated using Decision Matrix Analysis [5, 6]. New evaluation criteria were specified form the main factor, and relative-weighted using tree diagram method.

For the evaluation, following seven criteria were used.

1) Able to apply the fertilizer beneath the soil with a depth of 10-15 cm, in the root zone at a certain distance from the oil palm tree.
2) Able to load the required fertilizer (on the fertilizer hopper) the required amount (minimum for two row crops, for refilling on one side only).
3) Can be operated across the pathways of oil palm planting terrace.
4) The metering device and spreading system are suitable for the type of granular fertilizer
5) Can be operated across the pathways of oil palm planting terrace.
6) The fertilizer applicator unit is not a separate unit that is pulled (trailing) by the prime mover
7) Using a four-wheel tractor or a small crawler tractor available at the site, or can be provided by the company.
8) Has a high working capacity.
9) Low manufacturing cost and operation cost.
3. Results and discussion

3.1. Design Concepts
Based on the design criteria, several design concepts were studied and developed. Some principle mechanisms and fertilizer applicator design were studied, in generating the concepts. As a result five design concepts were proposed, including:
1. An applicator with left and right arms to distribute the fertilizer to the upper and lower terraces as shown in figure 3 (Concept-1)
2. An all-terrain vehicle equipped with a manually operated fertilizer injector (Concept-2)
3. An applicator equipped with a hole digger to place the fertilizer into the soil (Concept-3)
4. An applicator equipped with a shovel or a disk for making fertilizer furrows (Concept-4)
5. An applicator equipped with a rotary tiller to place and mix the fertilizer beneath the soil surface (Concept-5).

![Figure 3. Fertilizer application concept on two planting terraces (Concept-1).](image)

The first concept of fertilizer application system on sloping plantation as shown in figure 4, can apply fertilizer on the terraces using a two-channel system with a machine operated in the track of a terrace. The applicator’s arms spread fertilizer on both sides (upper and lower terraces). This concept can answer the steep slopes conditions, but using a complex mechanism, big in size, and difficult to operate the machine in young oil palm planting areas. The track used should be wide enough at least 2.5 m wide so that the machine can be stable running.

The second concept of fertilizer application method is using an injector mechanism that is manually positioned by the operator and using an all-terrain vehicle (ATV) or a motorcycle. The ATV is equipped with a trailer on the left side for carrying the fertilizer and the pneumatic mechanism unit. The third concept uses a digger mechanism for making holes on soil so that the fertilizer can be placed in the holes. Preparation of fertilizer holes can be carried out using a sharply-tapered wheel (can be a gear or the like). The hole depth is about 5 cm, the width of the digger point is about 8 cm, the number of holes is 20-30 holes per palm (considering the fertilizer application rate 2-3 kg/palm). Two concepts of fertilizer placement on the holes around the oil palm are shown in figure 4. An auger-type metering device is used for metering the fertilizer and a pneumatic system equipped with a blower is used for spreading and conveying the fertilizer to the holes.
Figure 4. Concepts of fertilizer placement on the holes around the oil palm of Concept-3: (a) straight pattern and (b) half circle curved pattern.

The fourth concept is similar to the third concept, except the fertilizer placement method. In this concept, the fertilizer is placed in a furrow cut by a shovel or a disc as shown in figure 5(a). In the fifth concept, the applicator is equipped with a rotary tiller to place and mix the fertilizer beneath the soil surface at a depth of 10 cm, as shown in figure 5(b).

3.2. Design evaluation result
In the screening step, all the five design concepts were evaluated using two questions as described above. Based on the question 1, the concept-1 was decided to be no feasible. The machine construction will be complex and the operation will be difficult especially for the young oil palm. The arms of the machine will disturb the palm frond. Discussion with the user resulted that the concept should be eliminated in the first step. However, four other concepts passed in this evaluation step.

To compare the remaining concepts, using the Pugh method, the design criteria was used as the evaluation criteria on the user requirements mentioned previously and selected. The power spreader that recently used in the company, was selected to be the initial datum. The Pugh concept selection matrix shown in table 4 resulted from the first analysis. As shown in table 4, the four concepts were superior to the datum. However, in the first run concept-4 and concept-5 have the same level of advantages.
Table 4. Pugh matrix for fertilizer applicator concepts (run #1).

| Article I. | Article II. | Criterion | The power spreader | Concept-2 | Concept-3 | Concept-4 | Concept-5 |
|-----------|-------------|-----------|--------------------|-----------|-----------|-----------|-----------|
| 1. Able to apply the fertilizer beneath the soil with a depth of 10-15 cm, in the root zone at a certain distance from the oil palm | | | D | + | + | + | + |
| 2. Able to load the required fertilizer | | | S | S | S | S | S |
| 3. Can be operated across the pathways of oil palm planting terrace | | | A | + | + | + | + |
| 4. The metering device and spreading system are suitable for the type of granular fertilizer | | | T | S | S | S | S |
| 5. Can be operated across the pathways of oil palm planting terrace | | | U | + | + | + | + |
| 6. The fertilizer applicator unit is not a separate unit that is pulled by the prime mover | | | M | - | + | + | + |
| 7. Using a four-wheel tractor or a small crawler tractor available at the site | | | - | + | + | + | + |
| 8. Has a high working capacity | | | - | - | S | S | S |
| 9. Low manufacturing cost and operation cost | | | + | S | S | S | S |

Two concepts have a different method of the fertilizer application. In the concept-4 the fertilizer is placed in a row formed by a disk or a shovel, however, in the concept-5 the fertilizer is placed and mixed with the soil using a rotary tiller. The most related criterion with this condition is the first criterion, i.e., the ability to apply the fertilizer beneath the soil with a depth of 10-15 cm, in the root zone at a certain distance from the palm. The criterion can be specified to be new criteria, including a) effectively mixed the fertilizer with the soil, b) fertilizer well covered by the soil, and c) not leaving the open furrow. The two concepts use a different mechanism for placing the fertilizer beneath the soil so that the manufacturing cost for the mechanism should be considered in the evaluation. According to these reasons, new following evaluation criteria then were used in the decision-making step:

a) effectively mixed the fertilizer with the soil \(O_{31}\),
b) fertilizer well covered by the soil \(O_{32}\),
c) not leaving the open furrow \(O_{33}\), and
d) low manufacturing cost for mechanism of fertilizer placement \(O_{22}\).

The weighted factors were decided using weighted tree diagram, as shown in figure 6. The evaluation criteria then were relatively scored for each concept, using 0-10 scale. To select the best concept among the two concepts, the weighted decision matrix was used as shown in table 5.
Figure 6. Weighted tree diagram for each evaluation criteria (objectives).

Table 5. Weighted decision matrix results.

| Criteria | a (O31) | b (O32) | c (O33) | d (O22) | Total |
|----------|---------|---------|---------|---------|-------|
| Concept-4| 3       | 4       | 4       | 10      | 5.45  |
| Concept-5| 10      | 6       | 10      | 3       | 7.34  |

As shown in table 5, the concept-5 is superior to the concept-4. Then, the concept-5 was decided to be the best design concept that will be developed further.

3.3. Design analysis
In accordance with the specifications and design limits that have been studied, the main function of the developed machine was: "applying granular NPK fertilizer to oil palms planted on terraces effectively". From the main function then sub-functions were developed. Alternative mechanisms and components for each function were proposed. The result of the functional design analysis is presented in table 6. Underlined mechanisms or components were selected to be implemented in the design of the fertilizer applicator.

To get the optimum design, each part and mechanism has been analyzed using proper design analysis methods, including:
1. Material strength analysis for each external loaded component, such as fertilizer hopper, framework of fertilizer hopper, shafts, rotary supporting frame, rotary lifting frame etc [7].
2. Power requirement analysis, to rotate the rotary blades, to lift the rotary frame, and to rotate the spinner of the fertilizer metering device.
3. The kinematic analysis of the rotary lifting frame of the rotary unit, which is driven by the hydraulic cylinders, and the kinematic analysis of the movement of the levers as well as the set of drive linkages for shifting the fertilizer metering disk.
4. Analysis of the size of fertilizer hopper, size of the spinner space, size of the fertilizer discharge gate at the bottom of the hopper.
5. Analysis of machine stability when operated on sloped land or track.
6. Machine working performance analysis and analysis of machine operating costs.
Table 6. Sub-functions and alternative mechanisms of the fertilizer applicator

| No. | Function/sub-function | Alternative mechanisms, components |
|-----|-----------------------|-------------------------------------|
| 1   | Store granular fertilizer | A hopper selected |
| 2   | Convey the fertilizer to the metering system | A tube, An open-closed gate selected |
| 3   | Meter the fertilizer according to the application rate and convey it to the targeted area | A grooved rotor type metering device, A centrifugal type metering device and a spinner selected |
| 4   | Hold the hopper and metering device unit | A frame selected |
| 5   | Drive and rotate the metering device | A power transmission system from tractor engine, A hydraulic motor selected, A gasoline engine, An electric motor, A shovel |
| 6   | Open furrows for placing the fertilizer, or loosening the soil and mix the fertilizer in the soil | A toothed wheel, A soil drill, A rotary tiller selected, A disk type furrow opener, A power transmission system from tractor PTO |
| 7   | Drive and rotate the mechanism for mixing the fertilizer in the soil | A hydraulic motor selected, A gasoline engine, An electric motor |
| 8   | Lifting and lowering the mechanism for mixing the fertilizer in the soil | A lifting frame using hydraulic cylinders selected, The three-point linkage of the tractor |
| 9   | Providing mechanical power for the prime mover | Tractor engine and a hydraulic power system selected |
| 10  | Operate the gate of the fertilizer metering device | A handle and its linkages selected |
| 11  | Support the operator when pouring fertilizer into the hopper | A support frame and a stepper selected |
| 12  | Support the load of all components of the fertilizer applicator | A frame selected |
| 13  | Drive and move the fertilizer applicator unit | A small four-wheeled tractor, A mini crawler tractor selected, An all-terrain vehicle (ATV) |
3.4. Construction design of the fertilizer applicator

As a result of oil palm fertilizer applicator design, 3D model has been created, as well as engineering drawings. The 3D model image of the proposed machine is shown in figure 7. The construction and drawings are shown in figure 8. The general specifications of the machine are presented in table 7. The final design concept of the fertilizer applicator uses a 110 cm wide mini crawler type tractor (Canycom S 160) as the prime mover. The machine is equipped with a hopper and a spinner disk for metering and conveying the fertilizer. The hopper capacity is 475 l that can store about 520 kg of NPK fertilizer. The spinner is rotated by a hydraulic motor (Rexroth MKM-32). A 20 cm wide rotary tiller is equipped in the front of the machine, to pulverize the soil and mix the fertilizer in the soil at a depth of 5-10 cm. Four rotary blades are installed on the rotary shaft which is rotated by a hydraulic motor (Rexroth MKM-32).

Table 7. General specifications of the fertilizer applicator.

| Specifications                                | Unit | Value          |
|----------------------------------------------|------|----------------|
| Weight of the machine (without ‘Canycom’)    | kg   | 187            |
| Weight of the machine with the ‘Canycom’      | kg   | 1300           |
| Length x Width x Height                      | cm   | 291 X 112 X 238|
| Hopper capacity                              | l (kg)| 475 (520)     |
| Prime mover                                  | Canycom S 160 |
| Engine Type                                  | 20.5 HP Diesel Engine |
| Hydraulic motor for rotary tiller and spinner| Rexroth MKM-32 |
| Operation speed                              | km/h | 0 - 7.5        |
| Working capacity                             | ha/h | 2-2.5          |

Figure 7. Three-D model of the fertilizer applicator for oil palm on terrace cultivation.
Figure 8. The construction of the fertilizer applicator.

4. Conclusions
The evaluation results showed that the concept of fertilizer applicator equipped with a rotary tiller had the most advantages on the expected design criteria. A 3D model and also the engineering drawing of the concept was developed. The design concept uses a 110 cm wide mini crawler tractor as the prime mover and is equipped with a hopper and a spinner disk for metering and conveying the fertilizer and a 20 cm wide rotary tiller in the front of the machine.

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