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High Precision Fertilizer Applicator for Industrial Plantation: Discrete Element Method Simulation and Prototyping

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Abstract

Fertilizer dose should meet the nutritional requirements of plants and be given uniformly, so that plant growth is more effective while reducing waste to the environment. This study aimed to design a high-precision fertilizer applicator to distribute fertilizer according to the required dose uniformly to every specified point. The fertilizer applicator was designed to have an auger and drive system that can discharge the fertilizer precisely. A 3D CAD model of the applicator was created to conduct a discrete element simulation to predict the discharge fertilizer process. An experiment was carried out to validate the simulation model. The experiment utilized a small-scale applicator prototype manufactured by 3D printing. A small electric actuator controlled by an Arduino microcontroller was installed to rotate the auger. The dose of the fertilizer discharged from the applicator can be adjusted by determining the number of auger rotations. Based on the analytical calculation, the applicator discharged fertilizer with a resolution of around 3.04 gr/rotation. Both simulation and experiment results were compared and showed a small error of 7.26%. The results show our designed fertilizer applicator has good accuracy and precision, which indicates the applicator was suitable to distribute fertilizer uniformly.

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1. Introduction

Fertilization is an important activity in the cultivation of industrial forest plantations (IFP) (Borges et al., 2016; Imanuddin et al., 2020). Fertilization is done twice: before planting and during plant maintenance activities. Fertilization aims to increase soil fertility but cannot be done freely. The addition of fertilizers can stimulate plant height, the number of plant leaves, and plant root length. The well-developed roots resulted in the good development of other parts of the plant since the roots can absorb more nutrients needed by the plant so that harvesting becomes faster (Wasaya et al., 2018).

If there is an error during fertilization, it can be fatal for the plant and become a waste. Fertilizers can cause dependence and can have an adverse impact, such as the soil becoming damaged and acidified, emission of greenhouse gas, and reduced efficiency of nutrient usage (Zhang, 2019). The widely used fertilizers are of the NPK and TSP types which have phosphor elements. Excess phosphor elements can be dissolved in rivers or lakes. The accumulation of phosphor and nitrate ions in rivers or lakes causes the uncontrolled growth of wild aquatic plants. This process is usually called eutrophication (Gilbert, 2017). However, if the dose of fertilizer given is less than it should be, it causes the soil to lack nutrients and the plants have slower growth and even die. Therefore, the dose of fertilizer must be in accordance with the plants and nutrients in the forest restoration site.

Fertilization activities are carried out in the area around the plant. In principle, the distance between the planting point and the fertilization point is adjusted to the diameter of the plant crown. In general, basic fertilizer application is spread with a certain spacing. This distance adjustment is made to facilitate fertilization activities and ensure that the fertilizer is not too close to the roots. Young plant's roots that touch the molten fertilizer are susceptible to death. In addition to the planting distance, dosing on plants needs to be considered because the dose of fertilizer can affect plant growth.

The dose given at one fertilization point with other fertilization points must be uniform. The fertilization process aims to accelerate plant development. If fertilization is not performed uniformly, the harvest schedule becomes different for each tree so that when the harvest schedule is set, there may still be trees that are not ready to be harvested (Moreno et al., 2017). Trees that are not ready to be harvested cannot be sold because they are not in accordance with the standard, so they must wait for the next harvest schedule. This can cause a loss of both time and land used in the industry. In fact, continuity during planting and harvesting is very necessary to improve the efficiency and performance of IFP (Rossit et al., 2021)

The activities that must be carried out in planting IFP are very complex and comprehensive and require large human resources. Human resources play an important role in carrying out the operational activities of the industry. Replanting forests requires a lot of laborers to dig the soil, place fertilizers and stockpile fertilizers considering that the area to be recovered is very large and the given time is very short. However, the industry that manages IFP usually has difficulties in finding a lot of workers to carry out the activities. Automation equipment is needed to overcome this problem (Engler et al., 2016).

Many researchers in the agroindustry seek to overcome the problem of fertilization (Lang et al., 2013; Shi et al., 2015; Van Loon et al. 2018). One of them is by making a fertilizer spreader automation tool to spread fertilizer quickly, accurately, and precisely. However, in practice, the use of this tool is still not effective because the dose cannot be adjusted, jams during operation, and the dose of fertilizer discharged is not precise. The usual disadvantage of using an applicator is that it is very low in flexibility, stability, and dosage that is low in uniformity and discharge rate (Jinfeng et al., 2018; Yinyan et al. 2017; Zhu et al. 2018).

A fertilizer applicator needs to be developed to be more flexible so that if the dose is changed, there is no need to change the components of the applicator. There are several issues that must be addressed in designing a fertilizer applicator such as (1) The dose given to plants affects plants and costs, (2) The dose given between plants in a field must be uniform, (3) The fertilizer application time is very short, (4) The number of workers is not much.

This research aims to design a prototype of a fertilizer applicator that can spread fertilizer according to the dose with high precision in which it can deliver a consistent dose during operation. The fertilizer applicator was targeted to be used by farmers. Regarding the different amounts of fertilizer required by every plant, the applicator was designed to discharge an adjustable amount of fertilizer dose. The fertilizer dose can be adjusted by determining the number of auger rotations of the applicator. Therefore, designing a minimum resolution of discharged fertilizer per rotation is an important aspect to achieve high accuracy.

The method of this study consisted of several processes. A fertilizer applicator model was first designed using CAD software with the main components being an auger, an actuator, and a controller. The fertilizer discharge mechanism is simulated using discrete element method software. The mass amount of fertilizer discharged from the applicator is then evaluated. After that, a prototype of the fertilizer applicator was made using 3d printing. The fertilizer discharge experiment was carried out with the same scheme as the simulation. The results from the simulation and experiment were compared and discussed.

2. Materials and Methods

2.1 Design and analytical calculation

The discharge rate of the fertilizer applicator was calculated analytically while designing the dimension of the applicator components. The parameters of applicator components were iterated to obtain minimum discharge rate resolution to achieve high precision and accuracy. The discharge rate of the applicator was stated in terms of the fertilizer mass discharged in every cycle of auger full rotation of 360°. The applicator discharged rate is governed by the equation (1) (ref).

$$Q_i = \pi(R_o{}^2 - R_c{}^2).\mathrm{P}.\Psi.\rho.\mathrm{C} \quad (1)$$

in which Qi is the applicator discharge rate in grams/rotation, R_o is auger radius, R_c is the shaft radius, P is the auger pitch, Ψ is loading coefficient of the fertilizer that is 0.25, ϱ is the fertilizer density of 1190 kg/m^3, and C is the auger orientation factor of 1, since the auger is horizontal. Based on iteration, the analytical discharge rate of the fertilizer applicator was 3.04 gr/rotation with R_o of 15 mm, R_c 7.5 mm, and P of 15 mm.

2.2 Discrete element method simulation

Discrete element simulation was carried out to model the fertilizer applicator in working state and observe the interactions between fertilizer particles and the geometry of the fertilizer applicator (Bangura et al., 2020). The utilization of discrete element method is widely used in agriculture field specially to model particulate materials such as fertilizer (Pasha et al. 2014). The use of discrete element simulation is expected to represent the actual event when the fertilizer applicator has been produced. A discrete element method software named EDEM from Altair was used in the simulations of the fertilizer that was modeled as spherical particles (Lv et al., 2013).

Parameters used in discrete element simulation include main parameters and coefficient parameters. The main parameters consist of density, Poisson ratio, and shear modulus, as shown in Table 1. Meanwhile, the coefficient parameters consist of the coefficient of restitution, the coefficient of static friction and the coefficient of rolling friction that was referred to the study by Ding et al. and shown in Table 2.

Tabel 1. Main parameters of NPK fertilizer (Ding et al., 2018)

Parameters	Value	Unit
Bulk density	1190	kg/m^3
Shear modulus	35.6	GPa
Poisson ratio	0.25	

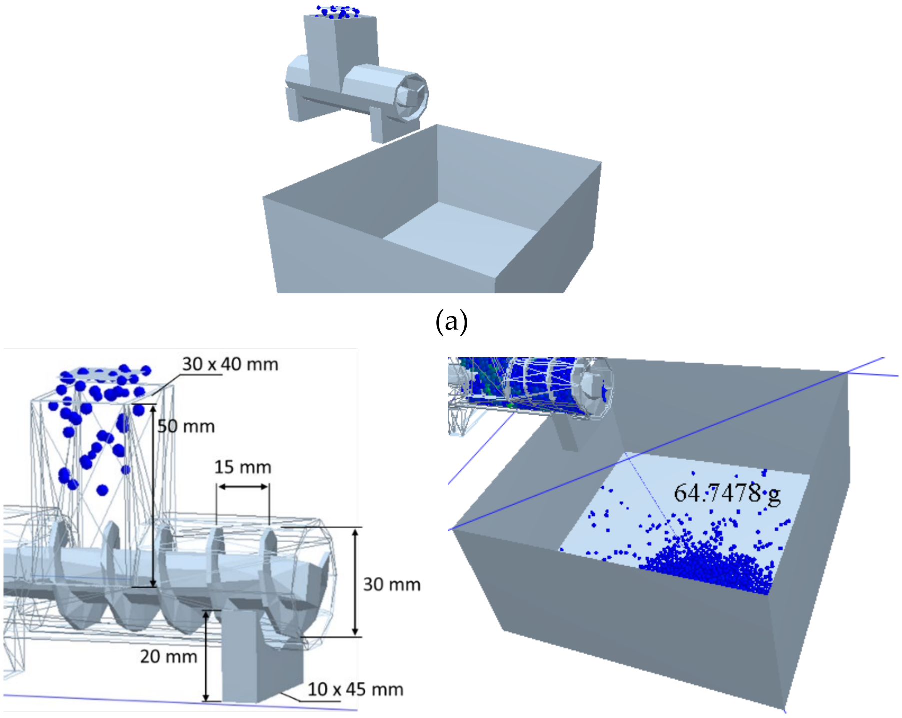
Tabel 2. Fertilizer coefficient parameters (Ding et al., 2018)

Parameters	Restitution coefficient	Static friction coefficient	Rolling friction coefficient
Between fertilizer particles	0.323	0.426	0.123
Fertilizer particle to applicator geometry	0.442	0.205	0.095

Discrete element simulation begins with designing the CAD model to be used in the simulation. The overall CAD model was created using Solidworks software and is shown in Figure 1(a). The applicator model was equipped with an auger to discharge the fertilizer in a controlled manner and a sensor in the container to measure the discharged fertilizer as can be seen in Figure 1(b) and 1(c), respectively. Each applicator component had been designed based on some considerations, such as the auger orientation determining the applicator efficiency, the auger dimension was determined by the fertilizer discharge rate and particle size which altogether determined the actuator power and channel dimension (Liping et al., 2018). The strength, manufacturability, and ease of assembly were also part of the considerations in designing the applicator components. In the EDEM software, the fertilizer bulk material parameters are shown in Table 3 and a particle size distribution of 2.25 – 4 mm is used. The CAD model that had been created was then imported into the EDEM software. Parameters of density, shear modulus, and Poisson's ratio of component material and bulk material were entered as input data, then the input friction coefficient parameter was entered. The simulation used a gravity of 9.81 m/s2. The factory feature that serves as the outlet for bulk materials was used with the input parameters of mass flow and the amount of mass of bulk material that can be discharged. The simulation results can calculate the mass of the discharged fertilizer by adding a mass sensor in the container.

Tabel 3. Characteristics of NPK fertilizers (Ismail, 2011)

Characteristics	Value
Bulk density (kg/m^3)	850-1190
Angle of repose (deg)	32
Friction Coefficient	0.5
Wall friction (deg)	28.5



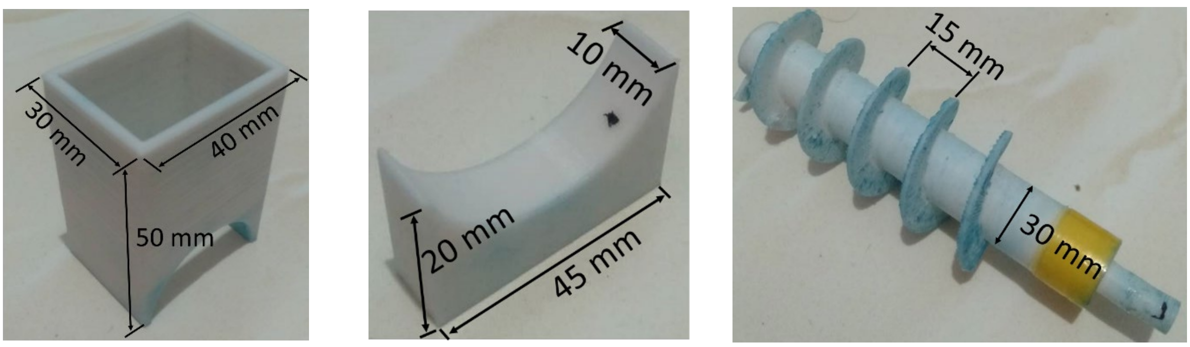
(a)

(b) (c)

Figure 1. (a) 3D CAD geometry of fertilizer applicator, (b) Detailed auger and (c) Mass sensor in discrete element simulation.

2.3 Prototyping and experiment

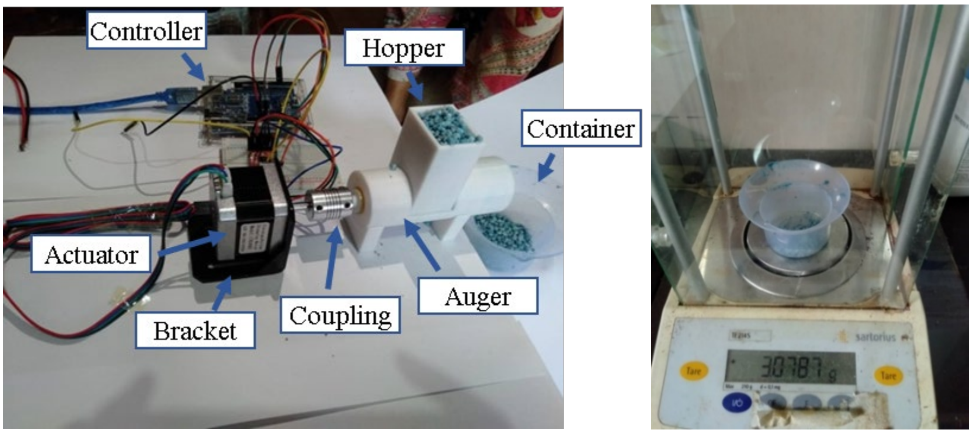
The experiment was carried out by performing a fertilizer discharge test using a prototype that was built based on the designed fertilizer applicator to validate the simulation results. The prototype utilized the same geometry and dimension as the simulation model, except the hopper was built on a small scale for simplicity, therefore the discharge rate of the applicator was not significantly affected. The applicator components were created by 3D printing using polylactic acid (PLA) as the material. The resulted fertilizer reservoir, holder, and auger components are shown in Figure 2(a), (b), and (c), respectively.



(a) (b) (c)

Figure 2. 3D printing results: (a) fertilizer storage, (b) holder, and (c) auger.

The experiment was carried out using auger, hopper, stepper actuator, A4988 driver, stepper actuator bracket, arduino controller, digital scales, adapter, and flexible coupling assembled as shown in Figure 3(a). The actuator used was a DC brush MOT-JGY370-12V150 with rated voltage of 12V, transmission ratio of 37.3:1. The A4988 driver had microstep resolution of full, 1/2, 1/4, 1/8, and 1/16, continuous current per phase of 1 A, logic input voltage of 3V - 5.5V, output voltage of 8V - 35V. The auger rotated by the actuator through a flexible coupling to discharge fertilizer from the hopper. An Arduino program was written for the actuator control algorithm. The controller used was Arduino UNO with operating voltage of 5V, recommended input voltage of 7-12V, DC current on I/O of 40mA, and frequency of 16 MHz. The condition of the hopper was kept constantly fulfilled with fertilizer to match the actual conditions where there is always fertilizer on top of the auger. The discharged fertilizer of each auger rotation was accommodated in a certain container and weighed using a digital scale. The weighing of the discharged fertilizers is shown in Figure 3 (b).

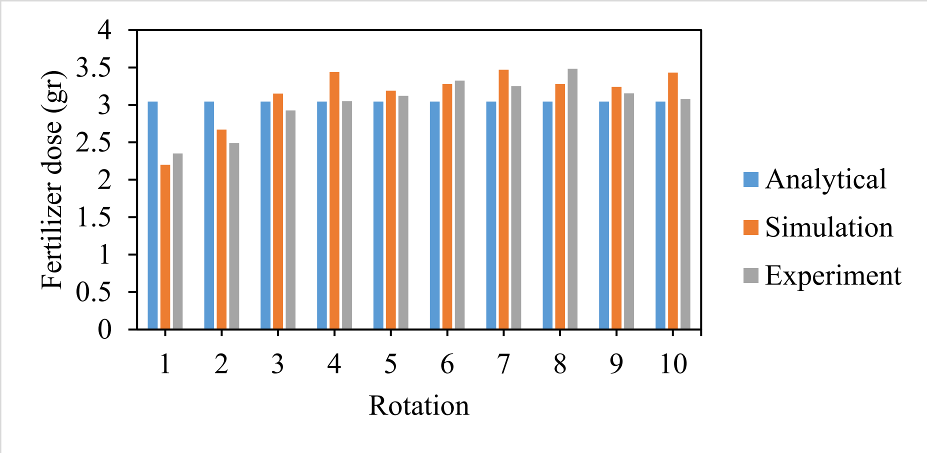


(a) (b)

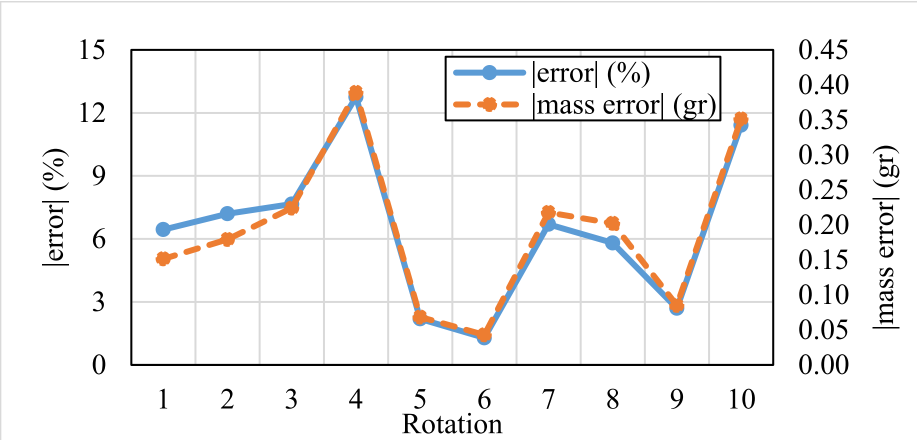
Figure 3. Components and installation of fertilizer applicator prototype and (b) weighing of discharged fertilizer.

3. Results and Discussion

The results of this study were analyzed based on analytical calculation, simulation, and experiment. The experiment of the fertilizer applicator prototype was carried out to validate the discrete element simulation results. Validation was carried out by comparing the fertilizer discharge rate from experiment and simulation. The simulation model was considered valid when the Normalized Root Mean Square Error (NRMSE) was less than 10% of the experimental results (Iqbal et al., 2014). Analytical calculation result was also added to the comparison to give an idea of the ideal condition. The results of the discharged fertilizer doses from analytical calculation, simulation, and experiment are shown in Figure 4(a). From the analytical calculation, the dose of fertilizer that can be discharged was calculated using equation (1) resulted around 3.04 gr/rotation. The simulation results showed the dose of fertilizer discharged varies from 2.2 gr/rotation – 3.47 gr/rotation. The experiment results showed the dose of fertilizer discharged from the applicator prototype varied from 2.35 gr/rotation - 3.48 gr/rotation.



(a)



(b)

Figure 4. Plot of (a) comparison of fertilizer doses (b) error of simulation vs experiment for each rotation.

To simplify the comparison and facilitate the validation process, the difference between experimental and simulation results was stated in terms of absolute percentage error and absolute mass error of each cycle calculated using equation (2) and (3) and shown in Figure 4(b).

$$|error|\ (\%) = \left|\frac{S_i - M_i}{M_i}\right| \times 100\% \tag{2}$$

$$|mass\ error|\ (gr) = |S_i - M_i| \tag{3}$$

Where S_i and M_i are the simulation and experiment result in i^{th} rotation, respectively. The error percentage was ranged between the minimum value of 1.29% to the maximum value of 12.76%. The error was quite small especially when considered in terms of mass which is 0.04 gr for the minimum value and 0.39 gr for the maximum value. The overall error between the simulation and experiment discharged dose was stated in terms of NRMSE using equation (4).

$$NRMSE = \sqrt{\frac{\sum(S_i - M_i)^2}{n}} \times \frac{100\%}{M} \tag{4}$$

where M is the average value of experiment results. The overall NRMSE was 7.26% which is considered excellent since the value was below 10% (Iqbal et al., 2014). Therefore, the discrete element simulation model was considered valid and can be used for further analysis.

From the comparison results, it was found that the dose of the first two rotations of simulation and experimental results are quite different from the analytical calculation results. This is due to the fact that fertilizer applicator has not reached steady state in the initial cycles. Therefore, the fertilizer applicator should be started up until it reached steady flow such that the fertilizer applicator can perform with high precision. For this study, based on the results, the simulation and experiment were considered steady starting from the third rotation and forth. During steady state, the dose of fertilizer discharged varies from 3.15 gr/rotation – 3.47 gr/rotation with an average of 3.31 gr/rotations for simulation. The results of the experiment during steady state, the dose of fertilizer discharged varies from 2.93 gr/rotation - 3.48 gr/rotation with an average dose of 3.17 gr/rotation. The steady state results of the simulation and experiment, that is 2^{nd} to 10^{th} rotation, showed a small NRMSE of 9.5% and 6.84% to the analytical calculation, respectively. The coefficient of variation for the discharge rate in steady state for the simulation and experiment was 0.034 and 0.051, respectively. Such low error to analytical result and low coefficient of variation indicates the fertilizer applicator have a good accuracy and precision and can be implemented to distribute the fertilizer uniformly.

The approximate fertilizer application speed of the applicator can be calculated based on the plant fertilizer requirement, auger fertilizer resolution and auger rotational speed. The fertilizer requirement for each plant was around 120 gr which applied to two holes on the sides of the plant. Therefore, each hole had to be applied with 60 gr of fertilizer. The applicator was planned to have two augers to apply fertilizer for each hole simultaneously. With auger resolution of 3.04 gr/rotation, the applicator needs 20 rotations to fill the hole with fertilizer with accuracy more than 98.5%. The auger speed of 100 rpm, made the fertilizer application time of 12s for each plant. The applicator specification met a good fertilizer applicator which is expected to provide fertilizer according to the amount specified by the operator based on the needs of the plants consistently and with minimum error.

4. Conclusion

A mechanical fertilizer applicator system has been designed. The fertilizer applicator uses an auger screw to push the bulk material towards the outlet. The dimensions of the auger and the shaft was iterated to obtain minimum discharge rate resolution of 3.04 gr/rotation in order to achieve high precision. Discrete element simulation has been carried out to model the fertilizer applicator in working state. The simulation model was validated by conducting simple experiment. The simulation results were concluded to be valid since the NRMSE value for the discharged dose between the experimental and simulation of all rotation was 7.26% which is below the specified value of 10%. In the first two rotations of the auger, the dose of the discharged fertilizer of the simulation as compared to the experiment shows large deviation since the applicator has not reached steady state. It is suggested to start the applicator until it reaches steady state before actually using it to distribute the fertilizer. In the steady state condition, the fertilizer applicator demonstrates a good accuracy and precision in both simulation and experiment.

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