Development of Grooved Belt Type Fertilizer Metering Mechanism for Spot Fertilizer Applicator

Abstract: Higher risks involved in excess fertilizer application require precise placement of fertilizer in adequate amount in the root zone of the crop. The drawbacks of current fertilizer application techniques (band placement, pellet application, and ring basin method) include over-fertilization, soil acidity, nutritional imbalances, soil structure damage and an increase in bulk density. Development of a spot fertilizer applicator with precise fertilizer metering was planned to address the problem. The physical and mechanical properties of di-ammonium phosphate were determined. A new grooved belt type fertilizer metering mechanism was developed for orchard application using the fertilizer properties determined. The metering mechanism was equipped with a fertilizer box of 100 kg capacity. The torque requirement of metering mechanism was determined using torque transducer to select a DC motor. The maximum torque required was 4.5 N.m at 8 $m.min^{-1}$ of metering belt speed. An automatic plant detection-based spot fertilizer applicator with developed fertilizer metering mechanism has potential to save about 20% fertilizer compared to band placement along with reduced labour requirement.

Keywords: Fertilizer properties, precision fertilizer metering, spot fertilizer application, torque measurement

Introduction

Growers and agronomists aiming for higher production, greater profitability, more effective conservation or improved sustainability using “4R” nutrient stewardship (right source, right rate, right time and right place). Spot fertilizer application using tractor mounted fertilizer applicator for orchard can help in achieving right amount fertilizer application at right place. Spot application of granular fertilizer requires higher precision because the fertilizer is applied only in the root zone of the plant. In this case any large variation in fertilizer metering can cause the damage to the plant compared to the broadcasting or band placement where the fertilizer application in done in larger area. Nguyen et al. (2020) had studied the effect of different material properties on mobility of granular flow, that is one of the important factors affecting the metering and dispensing of granular fertilizer in any system. The effectiveness of fertilizer application depends on the three main factors namely operator, application system and fertilizer properties (Fulton and Port, 2016). Thus, the first and most important step towards the development of any fertilizer equipment is the determination of fertilizer properties which assist in design of application system for efficient use of fertilizers.

Fertilizer application in orchards require larger metering capacity compared to field crops (Ganeshamurthy et. al., 2019). Conventional fertilizer metering mechanisms had either lower metering capacity or lower metering accuracy (Thorat et al., 2019; Jyoti et al., 2022). Therefore, a new metering mechanism was needed that can handle a higher application rate with precision.

Keeping this in view, physical and mechanical properties (size, shape, sphericity, bulk density, particle density, moisture content, angle of repose, crushing strength and coefficient of static friction) of diammonium phosphate (DAP) to be used in the development of spot fertilizer metering system for orchard crops were determined using the standard protocols. Due to larger variation in DAP granule properties, it causes difficulty in metering and dispensing. Therefore, DAP fertilizer was selected for the study. The properties determined were used for the design of fertilizer box, fertilizer metering and dispensing mechanism.

Various researchers presented the effect of different physical and mechanical properties of fertilizer on flow of granular fertilizer, design of fertilizer box and uniformity in metering.

Table 1. Effect of different fertilizer properties on fertilizer metering and dispensing

Sr. No.	Fertilizer properties	Effect on fertilizer metering and dispensing	Reference
1	Shape and Size	Affects the flowability of fertilizer and defines the bridging characteristics	Beverloo et al., 1961; Aphale et al., 2003
2	Bulk density and particle density	Most important parameter for metering mechanism, helps in determining size of fertilizer box	Garcia et al., 2012; Galvao et al., 2018; Hofstee, 1993
3	Moisture content	Affects the density and friction characteristics of fertilizer	Hofstee, 1993
4	Angle of repose	Important to design the bottom of fertilizer box	Beverloo et al., 1961; Garcia et al., 2012
5	Crushing strength	Important for smooth working of metering mechanism	Walker et al., 1997
6	Coefficient of static and dynamic friction	Affects the design of fertilizer box	Grift, et al., 2006; Savenkov et al., 2019

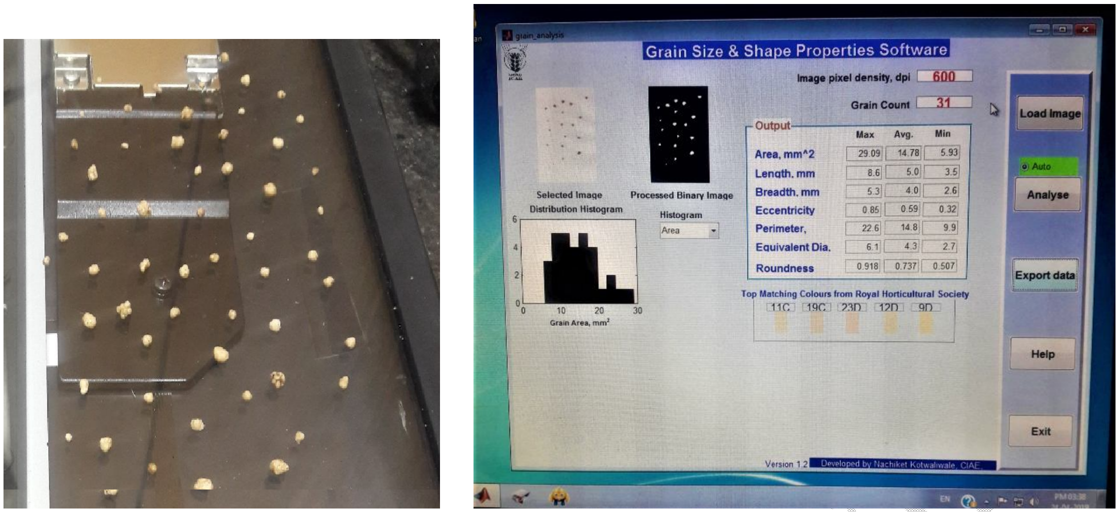
Materials and Methods

Determination of physical and mechanical properties of DAP (Di-ammonium Phosphate):

1. **Shape and Size:** The shape of the fertilizer granules can be expressed by their roundness and sphericity. These properties do interfere with the flowing and bridging behavior of the fertilizers. The projected area, length, breadth, eccentricity, perimeter, equivalent diameter and median width of the fertilizer granules were measured by image processing using MATLAB based grain shape and size properties software developed at ICAR-CIAE, Bhopal. The area of the smallest circumscribing circle was calculated by taking the largest axial dimension (diameter of circle) of the fertilizer granules when it was at natural rest position. Fertilizer granule dimensions were also measured manually in three axial directions using digital vernier caliper to validate the values obtained by the image processing. Sphericity of the granular particles was calculated using following formula:

$$\textbf{Sphericity}= \frac{\textbf{Geometric mean diameter}}{\textbf{major dimension}} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

$$\textbf{Sphericity} = \frac{(l \times b \times t)^{1/3}}{l} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$



Grain Size & Shape Properties Software

Image pixel density, dpi: 600

Grain Count: 31

Output

	Max	Avg.	Min
Area, mm^2	29.09	14.78	5.93
Length, mm	8.6	5.0	3.5
Breadth, mm	5.3	4.0	2.6
Eccentricity	0.85	0.59	0.32
Perimeter,	22.6	14.8	9.9
Equivalent Dia.	6.1	4.3	2.7
Roundness	0.918	0.737	0.507

Histogram: Area

Top Matching Colours from Royal Horticultural Society: 11C 19C 23D 12D 9D

Figure 1. Shape and size determination of DAP granules using Grain size and shape properties software

The shape and size parameters of DAP granules were measured using manual as well as MATLAB based grain size and shape properties software. The equivalent diameters of the sample data were analysed using paired sample t-test in SPSS software

2. **Bulk Density:** The bulk density of granular fertilizer is the ratio of weight and volume of the fertilizer including the space between individual particles. The bulk density of the fertilizer was important for the determination of hopper volume. A measuring cylinder with least count of 0.5 ml (0.5 cm^3) was used for determination of bulk density. The sample was filled in the cylinder and the volume was measured. Thereafter, the sample was weighed using precision weighing balance. The experiment was replicated five times for different samples.
3. **Particle Density**: Liquid (water) displacement method is generally used for particle density measurement (Webb, 2001). But this method has its own limitation as fertilizer can absorb the water. Thus, this method can't be used for determination of fertilizer particle density. Water absorption by fertilizer granule can be prevented using the of molten paraffin wax of know density (0.78 $g.cm^{-3}$). A layer of paraffin wax was coated around the fertilizer granules by dipping the known amount of fertilizer and kept in open air till the wax was frozen. Fertilizer granules with wax coating were weighed using precision weighing balance. A known volume of water was filled in the measuring cylinder. Wax coated fertilizer granules were submerged in the water filled measuring cylinder. The displacement of water by the wax coated fertilizer was measured. Volume of wax was calculated by the following equation:

$$\boldsymbol{V_w = \frac{W_f - W_{fw}}{\rho_w}} \qquad \text{…………..(4)}$$

Then the particle density of fertilizer was calculated using the following equation:

$$\boldsymbol{\rho_{fp} = \frac{W_f}{V_{fw} - V_w}} \qquad \text{………(5)}$$

Where, V_w is volume of wax coating (cm^3), W_f is the weight of fertilizer sample (g), W_{fw} is the weight of fertilizer sample with wax coating (g), ρ_w is the density of wax ($g.cm^{-3}$), ρ_{fp} is the particle density of fertilizer sample ($g.cm^{-3}$) and V_{fw} is the volume of fertilizer sample with wax coating (cm^3)

4. **Moisture Content:** Moisture content of the fertilizer was determined using hot air oven method. Empty glass bottles with cork lid were cleaned and weighed (W_g) using precision weighing balance. Bottles were partially filled with fertilizer samples and weighed (W_{s1}) using precision weighing balance. The samples were kept in oven with lid open at a temperature of 100±2°C for 3 hours (Deo et al., 2013). The samples were placed inside the desiccator with silica gel after the oven drying to prevent regain of moisture. The fertilizer samples with bottle were weighed after temperature reduced to normal (W_{s2}).

$$MC\ (db)\% = \frac{(W_{s1} - W_g) - (W_{s2} - W_g)}{(W_{s2} - W_g)} \times 100 \qquad \text{.......(6)}$$

Where, W_{s1} is the weight of fertilizer sample with glass bottle before oven drying (g), W_{s2} is the weight of fertilizer sample with glass bottle after oven drying (g) and W_g is the weight of empty glass bottle (g).

5. **Angle of repose:** The angle of repose or critical angle of repose of a granular material is the steepest angle of descent or dip relative to the horizontal plane to which a material can be piled without slumping. It was determined using a setup with hopper and collection pan (Figure 2-a).

$$\theta = \tan^{-1}\left(\frac{2h}{b}\right) \qquad \text{..........(7)}$$

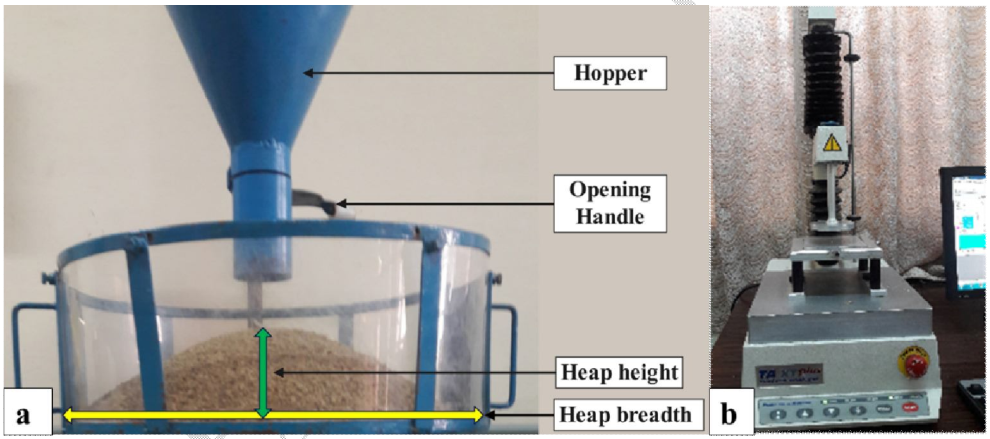


Figure 2. Angle of repose and crushing strength measurement

6. **Crushing strength:** It is defined as the force required for crushing the fertilizer granule between two plates. It was measured using texture analyzer by placing single grains between the two plates (Figure 2-b). The dimetric compression method of single granules was used for measurement of crushing strength.

7. **Coefficient of static friction:** It is defined as the friction force between two objects when neither of the objects is moving. The coefficient of static friction was determined using inclination plan method. MS (Mild steel), aluminium, green PVC (Polyvinyl chloride) and plywood sheets were used for the measurement of static friction. The inclination angle (φ) was recorded and the tangent of angle was taken as the coefficient of static friction.

$$\mu_s = \tan\varphi \qquad \text{.........(8)}$$

Design of fertilizer metering mechanism

A new metering mechanism was developed using multiple grooved green PVC belt. The endless belt was mounted over nylon roller. Two pillow bearings were used to support the shaft over which the nylon rollers were mounted. The thickness of belt was 3 mm. The shaft at the dispensing end was powered with DC motor. The metering belts had a groove volume of 50 cm^3. The amount of fertilizer delivered per groove can be calculated using the bulk density of fertilizer.

Design of gravity flow fertilizer box

A fertilizer box of 0.1 m^3 capacity was designed using the determined fertilizer properties (Varshney et al., 2004). The angle repose was 30° for DAP fertilizer. Therefore, the half angle of conical bottom in fertilizer box was 30°. The bottom opening was kept 50 mm to allow free flow of fertilizer required for metering (Figure 3). The diameter of top loading was 500 mm. The total height of fertilizer box was 900 mm (500 mm cylindrical section and 400 mm conical section).

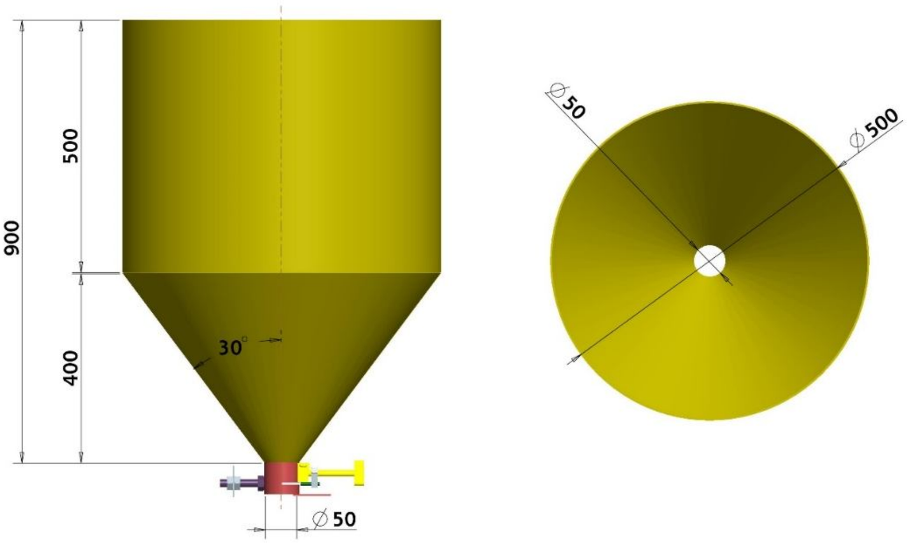


Figure 3. Views of fertilizer box (all dimensions in mm)

Torque measurement of the metering mechanism: The driving shaft of the metering mechanism was connected to a variable frequency drive (VFD) controlled electric motor using belt and pulley drive (Figure 4). A precision torque transducer (HBM T22/1 kN.m) was connected between electric motor and driving shaft. The data was recorded using HBM datalogger (MX840B, 8 channel). The experiment was conducted for three linear speeds (8, 9 and 10 $m.min^{-1}$) of the metering belt. The means of the torque values for different metering belt speed were compared using paired sample t-test in SPSS software.

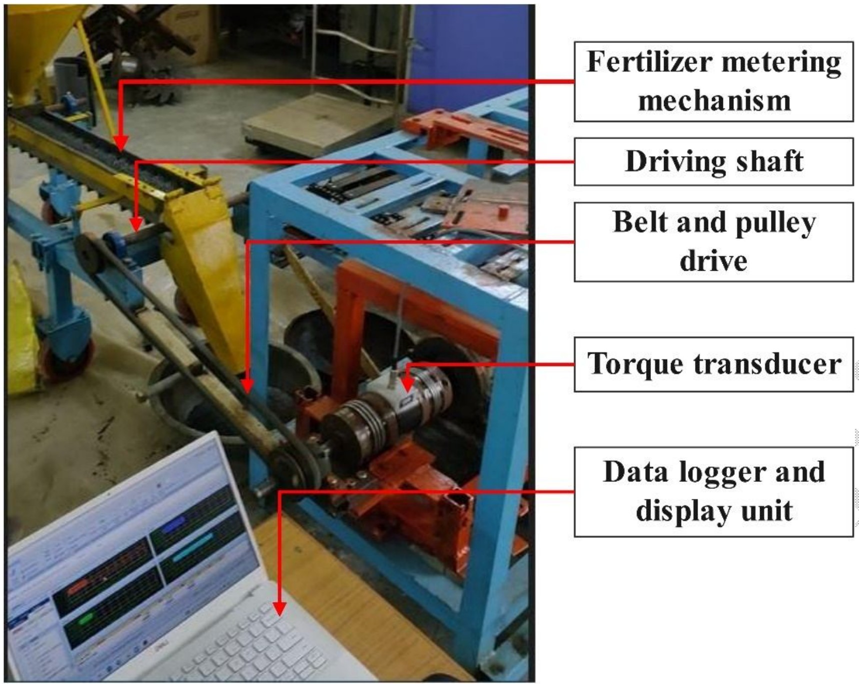


Figure 4. Torque measurement using HBM torque transducer

Results and discussion

The physical and mechanical properties of fertilizer (DAP) determined for the design of spot fertilizer applicator are presented in table 2.

Table 2. Physical and mechanical properties DAP granules:

Sl. No.	Fertilizer property	Mean	CV
1	Length, mm	3.241±0.02175	0.067
2	Width, mm	2.745±0.01993	0.073
3	Thickness, mm	2.414±0.0135	0.056
4	Equivalent Diameter, mm	2.763±0.01688	0.061
5	Eccentricity, mm	0.857±0.0026	0.030
6	Sphericity	0.863±0.00094	0.011
7	Angle of repose, degree	30.194±0.76895	0.057
8	**Coefficient of static friction**		
8.1	MS Sheet	0.422±0.00599	0.032
8.2	Aluminium Sheet	0.354±0.00439	0.028
8.3	Green PVC Sheet	0.323±0.00361	0.025
8.4	Plywood	0.437±0.00388	0.020
9	Bulk Density, g.cm^{-3}	1.013±0.01072	0.024
10	Particle density, g.cm^{-3}	1.554±0.02413	0.035
11	**Compression force, N**		

11.1	Small particle (2.1 mm)	44.286±3.51866	0.178
11.2	medium particle (4.2 mm)	90.714±7.57502	0.187
11.3	large particle (6.1 mm)	130.714±6.38077	0.109
12	**Crushing Strength, N.mm^{-2}**		
12.1	Small particle (2.1 mm)	12.51±0.99397	0.178
12.2	medium particle (4.2 mm)	6.597±0.55091	0.187
12.3	large particle (6.1 mm)	4.542±0.22171	0.109
13	Moisture content, %db	0.163±0.00099	0.014

The measured values of shape and size parameters of DAP granules using manual as well as MATLAB based grain size and shape properties software were also compared using paired sample t-test and were found not significant (Table 3). Therefore, it was evident that the grain size and shape properties software was accurate enough to measure the shape and size of granular fertilizer.

Table 3. Pair t-test for comparing means of equivalent diameters:

	Mean	SD	SEM	Median	t-value	Prob>|t|
MATLAB based measurement	2.79446	0.96581	0.03956	2.7	1.1298	0.25902
Manual measurement	2.77886	0.65744	0.02693	2.7		

The metering mechanism and the fertilizer box were designed using the determined physical and mechanical properties of DAP fertilizer. Angle of repose and bulk density were used for design of fertilizer box. Coefficient of static friction, bulk density and crushing strength were used for designing the metering mechanism and selection of material for metering belt. The detailed specifications of the developed system are shown in Table 4.

Table 4. Selected design parameters of metering mechanism for spot fertilizer applicator

S. No.	Parameters	Selected specifications
1	Fertilizer hopper volume, m^3	0.1
2	Hopper bottom angle, degree	60
3	Hopper bottom opening, mm	50
4	Metering belt material	Green PVC
5	Metering belt thickness, mm	3
6	Metering groove volume, cm^3	50
7	Metering belt width, mm	100
8	Length of endless metering belt, mm	2100
9	Nylon roller diameter: inner and outer, mm	25 and 50
10	Nylon roller length, mm	110
11	DC Motor torque, N.m	8.5

Torque requirement of the metering mechanism: The developed metering mechanism was operated using VFD. The torque transducer was connected between electric motor and driving shaft of metering mechanism. The torque required for idle operation (at 8 m.min^{-1}) was compared with full load operation of metering mechanism at 8, 9 and 10 $m.min^{-1}$ of metering belt speed (Table 5). The comparison showed significant difference between no-load and full load condition for all the speeds. The torque requirement at different metering belt speed also varied significantly.

Table 5. Pairwise comparison of torque requirement at different loads and linear speeds

Pairs	Mean difference	SD	SEM	t-value	df	Prob>|t|
Idle – 8 $m.min^{-1}$	-2.18753	0.27617	0.02247	-97.334	150	<0.00001
Idle – 9 $m.min^{-1}$	-1.71544	0.2574	0.02095	-81.894	150	<0.00001
Idle – 10 $m.min^{-1}$	-1.16271	0.24393	0.01985	-58.571	150	<0.00001
8 – 9 $m.min^{-1}$	0.47208	0.22877	0.01862	25.357	150	<0.00001
8 – 10 $m.min^{-1}$	1.02482	0.22105	0.01799	56.969	150	<0.00001
9 – 10 $m.min^{-1}$	0.55274	0.13701	0.01115	49.573	150	<0.00001

The torque requirement was maximum at 8 $m.min^{-1}$ linear speed of metering belt followed by 9 and 10 $m.min^{-1}$ speeds (Figure 5). The starting torque was 20% higher than the running torque at a constant linear speed of the metering belt. The higher starting torque is useful in determining the size of the motor.

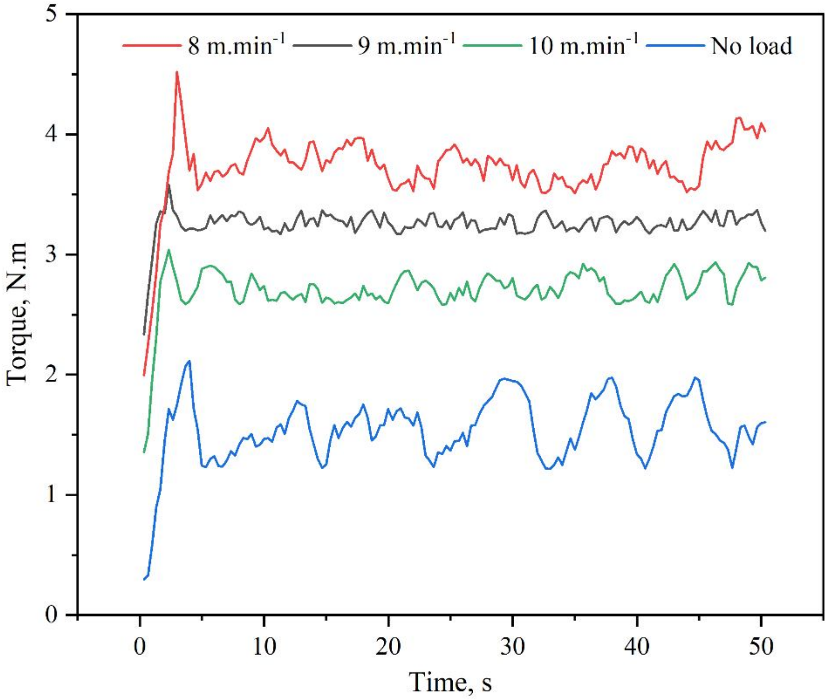


Figure 5. Variation in torque requirement of developed metering mechanism

Conclusion: Physical and mechanical properties of fertilizer were determined to design a metering mechanism for spot fertilizer application. A high capacity, precise fertilizer metering mechanism for orchard crop was designed that can deliver upto 1000 g of fertilizer per plant. The designed fertilizer box can store 100 kg of fertilizer during field application while ensuring sufficient granule flow to support the metering mechanism. The metering mechanism required a maximum of 4.5 N.m torque for smooth running. An 8.5 N.m DC motor with precise angular control can meet the torque requirement of the developed metering mechanism. An electronic sensing-based spot fertilizer applicator with grooved belt type metering mechanism can solve the problem of excess fertilizer application thus reducing the environmental hazard.

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