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Article

Design, Modeling, and Performance Evaluation of a Manual Gravitational Fertilizer Spreader with Linear Kinetic Energy Transmission System

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Abstract

The development of small-scale mechanization equipment for hand-cultivated farms and mountainous regions is essential for improving productivity in the agricultural sector. This research focuses on the design, construction, and evaluation of an innovative manual fertilizer spreader that operates without an external power source, based on the principles of gravitational flow and linear kinetic energy transfer. The system consists of a 20-liter backpack hopper, a flow control valve, a flexible guidance tube, and a 1-meter rigid launch tube. The flow mechanism was modeled based on Beverloo's Law, and energy transfer was modeled using Newton's Second Law and the Work-Energy Principle. Field tests in paddy fields of IRAN Golstan province showed the device, weighing under 1 kg, is capable of spreading fertilizer over 1.5 hectares per hour with a dispersion radius of 4 meters. Results indicate that a launch angle of 45 degrees and a horizontal oscillation range of 135 to 140 degrees provide the optimal conditions for a distribution uniformity of 78%.

Keywords: manual fertilizer spreader; Beverloo's Law; linear acceleration; oscillating launch tube; granular distribution; small-scale mechanization; projectile motion; gravitational flow; distribution uniformity

1. Introduction

Agricultural mechanization, as the cornerstone of sustainable agricultural development, plays a decisive role in increasing productivity and reducing production costs. According to the Food and Agriculture Organization of the United Nations, over sixty percent of farms in developing countries are smaller than two hectares, where the use of heavy machinery faces significant limitations. In Iran, based on statistics from the Ministry of Agriculture Jihad, approximately fifty-five percent of farms are classified as small-scale, and many farmers, especially in paddy, mountainous, and orchard farms, still rely on traditional manual methods of fertilizer and seed spreading. Traditional manual fertilizer spreading faces numerous challenges. Non-uniform distribution, typically with a coefficient of uniformity less than fifty percent, leads to input waste and reduced application efficiency. Studies by Parish and colleagues have shown that improper fertilizer distribution can reduce input efficiency by up to thirty percent. Ergonomically, this method is strenuous for the operator and involves a metabolic energy consumption exceeding four hundred and fifty kilojoules per hectare, leading to early fatigue and reduced work quality. Numerous efforts have been made to develop manual fertilizer spreaders. Most of these devices are designed based on spinning disc or centrifugal systems, which use gearboxes and complex mechanisms to generate centrifugal force. The Echo G-9 model, one of the commercial examples, has had limited acceptance among farmers due to its high weight, complex mechanism, and lack of precise control over the distribution pattern. Aphale and colleagues showed that in spinning disc systems, minor variations in particle physical properties such as size, shape, and moisture can severely affect the distribution pattern. Regarding the gravitational flow of granular materials, Beverloo and colleagues in 1961 provided a semi-empirical relationship for predicting the particle discharge rate from restricted orifices, which has since been used as the

primary basis for designing silos and discharge systems. Studies by Nedderman and Tüzün have shown that this law predicts flow behavior with acceptable accuracy for a wide range of agricultural materials. Mankoc and colleagues emphasized that when the orifice diameter is more than five times the particle diameter, the discharge rate is independent of the material column height.

The main objective of this research is to design and develop a manual fertilizer spreader with a simple architecture, low weight, and high efficiency, operating based on the principles of classical physics: gravity and linear kinetic energy transfer. The main innovation of this system lies in using a launch tube with linear oscillating motion instead of complex rotational mechanisms, enabling simultaneous control of the application rate and distribution pattern. Given the simple design, lack of need for an external power source, and low production cost, this system has high potential for widespread adoption among smallholder farmers and small farms.

2. Methodology

2.1. System Architecture and Component Specifications

The designed system consists of four main parts whose integrated operation ensures efficient fertilizer spreading. The storage hopper is made of high-density polyethylene with a 20-liter capacity and is designed in a backpack form, providing comfortable carrying and proper weight distribution on the operator's shoulders. The internal geometry of the hopper is cylindrical with a diameter of two hundred and fifty millimeters and a height of four hundred millimeters, terminating at the bottom in a conical shape with a sixty-degree slope angle to facilitate particle flow towards the exit valve. High-density polyethylene was chosen due to its suitable chemical resistance against chemical fertilizers, low specific weight, and acceptable mechanical strength.

The flow control valve is located at the end of the conical part of the hopper and consists of a sliding plate with continuous adjustment capability. This valve allows control of the effective exit diameter from five to fifteen millimeters, which can be adjusted according to the size of different fertilizer or seed particles. An optional sweeping mechanism, which can be installed between the valve and the hopper, consists of a flexible rod connected to the launch tube that sweeps the valve surface with the tube's movement, preventing particle accumulation or adhesion. However, tests have shown that for most dry fertilizers, this mechanism is not necessary.

The guidance tube is made of flexible rubber with an internal diameter of thirty-five millimeters and a length of two hundred millimeters, connecting the control valve to the launch tube. The flexibility of this tube allows free movement of the launch tube without applying stress to the valve. The slope of this tube is negative at rest to prevent automatic particle flow. The launch tube is made of rigid PVC with an internal diameter of thirty-five to forty millimeters and a length of one meter. This tube is responsible for transferring kinetic energy to the particles. At the end of this tube, a hose piece ten centimeters long, with an uneven internal surface and a vertical elliptical cross-section, is installed, responsible for creating random motions and increasing the particle dispersion area.

2.2. Gravitational Flow Modeling Based on Beverloo's Law

The flow of granular materials through restricted orifices is one of the complex phenomena in particle mechanics, whose behavior is influenced by orifice geometry, particle physical properties, inter-particle forces, and the stress field within the bulk. Extensive experimental studies have shown that under free-flow conditions, the discharge rate is independent of the material column height in the hopper, a phenomenon due to the formation of an active flow zone above the orifice. In this zone, particles are subjected to a homogeneous stress field and move towards the orifice at a relatively constant velocity. Beverloo's Law, a semi-empirical relationship, predicts the mass flow rate as follows:

$$W = C\rho_b\sqrt{g}(D_o - kd_p)^{5/2} \quad (1)$$

In this equation, W is the mass flow rate in kilograms per second, C is the dimensionless discharge coefficient depending on compaction, shape, and surface properties of the particles, typically in the range of 0.55 to 0.65 for common agricultural materials, ρ_b is the bulk density of the particle mass in kilograms per cubic meter, representing the mass per unit volume including void space between particles, g is the gravitational acceleration equal to 9.81 meters per second squared, D_o is the exit orifice diameter in meters, k is the dimensionless friction coefficient depending on orifice geometry, particle shape, and wall friction coefficient, typically in the range of 1.5 to 2.5, and d_p is the equivalent particle diameter in meters.

The exponent 5/2 in the above equation is derived from dimensional analysis and fitting extensive experimental data. The term $(D_o - kd_p)$ represents the effective orifice diameter, obtained by subtracting a characteristic length related to the particles from the geometric orifice diameter. This correction is necessary to account for the effect of the particle boundary layer near the orifice edge. To ensure the non-formation of arches or bridging that would block the flow, the following fundamental condition must be met:

$$D_o \geq 5d_p \quad (2)$$

This condition guarantees that multiple particles can simultaneously be present in the orifice cross-section, minimizing the probability of forming resistant structures that block the flow. To calculate the total emptying time of a hopper with volume V and assuming a constant discharge rate according to Beverloo's Law, the following relationship is used:

$$T_{empty} = \frac{V\rho_b}{W} = \frac{V\rho_b}{C\rho_b\sqrt{g}(D_o - kd_p)^{5/2}} = \frac{V}{C\sqrt{g}(D_o - kd_p)^{5/2}} \quad (3)$$

This equation shows that the emptying time is directly proportional to the hopper volume and inversely proportional to the effective orifice diameter to the power of 5/2. For a cylindrical hopper with diameter D and height H , the volume is calculated as $V = \frac{\pi D^2 H}{4}$. The volumetric flow rate is also obtained by dividing the mass flow rate by the bulk density:

$$Q = \frac{W}{\rho_b} = C\sqrt{g}(D_o - kd_p)^{5/2} \quad (4)$$

This relationship is essential for designing the flow control valve because by adjusting D_o , the fertilizer application rate can be controlled.

2.3. Dynamics of Linear Kinetic Energy Transfer to Particles

After particles exit the control valve and enter the launch tube, the kinetic energy transfer mechanism becomes active. The launch tube is subjected to horizontal oscillatory motion by the operator with an angular amplitude θ_{max} and frequency f . In this motion, the tube applies linear acceleration to the particles inside it, leading to an increase in their velocity. According to Newton's Second Law, the tangential force on a particle with mass m moving along the tube is as follows:

$$F_t = ma_t = m \frac{dv}{dt} \quad (5)$$

In this equation, F_t is the tangential force in Newton's, a_t is the tangential acceleration in meters per second squared, and v is the particle velocity along the tube in meters per second. Using the chain rule and the relationship $v = \frac{ds}{dt}$, where s is the particle position along the tube, we can write:

$$F_t = m \frac{dv}{ds} \frac{ds}{dt} = mv \frac{dv}{ds} \quad (6)$$

Separating variables and multiplying both sides by ds :

$$F_t ds = mv dv \quad (7)$$

Now integrating from the initial position s_1 with velocity v_1 (usually negligible initial velocity) to the final position s_2 with velocity v_2 at the end of the tube:

$$\int_{s_1}^{s_2} F_t ds = m \int_{v_1}^{v_2} v dv = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2 \quad (8)$$

The left side of this equation is the work done by the tangential force $U_{1 \rightarrow 2}$, and the right side is the change in the particle's kinetic energy ΔT . Therefore, the work-energy principle for particles inside the launch tube is written as follows:

$$T_2 = T_1 + U_{1 \rightarrow 2} \quad (9)$$

where kinetic energy is defined as $T = \frac{1}{2}mv^2$. For the case where particles enter the tube with negligible initial velocity ($v_1 \approx 0$), the final kinetic energy equals the work done by the tube force. If the tube moves with an average linear acceleration \bar{a} over length L , the average force on the particle is $F_t = m\bar{a}$ and the work done is:

$$U_{1 \rightarrow 2} = F_t L = m\bar{a}L \quad (10)$$

Therefore, the final particle velocity is:

$$v_2 = \sqrt{2\bar{a}L} \quad (11)$$

This relationship shows that the exit velocity of the particles is proportional to the square root of the product of the tube acceleration and its length. For simple harmonic oscillatory motion with angular amplitude θ_{max} and frequency f , the maximum acceleration at the end of the tube with length L is:

$$a_{max} = L\omega^2 \sin(\omega t)|_{max} = L(2\pi f)^2 \quad (12)$$

where $\omega = 2\pi f$ is the angular velocity in radians per second. Assuming an oscillation frequency of 0.77 Hz and a tube length of one meter:

$$a_{max} = 1.0 \times (2\pi \times 0.77)^2 \approx 23.3 \text{ m/s}^2 \quad (13)$$

Using the effective average acceleration, which is about half of the maximum acceleration ($\bar{a} \approx 0.5a_{max} \approx 11.7 \text{ m/s}^2$), and a tube length of one meter:

$$v_2 = \sqrt{2 \times 11.7 \times 1.0} \approx 4.8 \text{ m/s} \quad (14)$$

This theoretical velocity is in good agreement with experimental observations. It should be noted that friction between particles and the tube wall reduces the energy transfer efficiency, which can be considered with an efficiency coefficient η of about 0.7 to 0.8.

2.4. Projectile Motion Analysis and Range Calculation

After particles exit the end of the launch tube with velocity v_0 and angle θ_0 relative to the horizontal, they undergo projectile motion under the influence of gravity. Assuming negligible air resistance for particles with a diameter of two to three millimeters and average velocities, the equations of motion in the Cartesian coordinate system are as follows:

$$x(t) = v_0 \cos \theta_0 \cdot t \quad (15)$$

$$y(t) = v_0 \sin \theta_0 \cdot t - \frac{1}{2} g t^2 \quad (16)$$

where x is the horizontal distance and y is the height from the launch point in meters, and t is time in seconds. By eliminating the time parameter from the above equations, the projectile trajectory equation is obtained:

$$y = (\tan \theta_0)x - \left(\frac{g}{2v_0^2 \cos^2 \theta_0} \right) x^2 \quad (17)$$

This equation is a parabola representing the particle's path in the vertical plane. To calculate the horizontal range (the distance at which the particle reaches the ground level), we apply the condition $y = 0$:

$$0 = (\tan \theta_0)x - \left(\frac{g}{2v_0^2 \cos^2 \theta_0} \right) x^2 \quad (18)$$

Eliminating the trivial solution $x = 0$ (launch point), the range is obtained as follows:

$$R = \frac{2v_0^2 \cos^2 \theta_0 \tan \theta_0}{g} = \frac{v_0^2 \sin (2\theta_0)}{g} \quad (19)$$

This equation shows that for a constant initial velocity, the maximum range occurs at an angle where $\sin (2\theta_0) = 1$, i.e., $\theta_0 = 45^\circ$. The maximum height of the projectile is obtained from the condition $\frac{dy}{dt} = 0$:

$$H_{max} = \frac{v_0^2 \sin^2 \theta_0}{2g} \quad (20)$$

For an exit velocity of 4.8 meters per second and an angle of 45 degrees, the theoretical range is:

$$R_{45^\circ} = \frac{(4.8)^2 \times 1}{9.81} \approx 2.35 \text{ m} \quad (21)$$

Field tests showed an effective range of four meters, a difference primarily due to the effects of the end hose, which causes secondary particle dispersion and increases the coverage area.

2.5. Modeling Dispersion Pattern and Distribution Uniformity

To quantitatively evaluate the fertilizer distribution pattern, the Christiansen uniformity coefficient, one of the standard indices for evaluating spreading systems, is used. This coefficient is calculated based on the absolute deviation of measured values from the mean:

$$CU = 100 \left(1 - \frac{\sum_{i=1}^n |x_i - \bar{x}|}{n\bar{x}} \right) \quad (22)$$

where CU is the uniformity coefficient in percent, x_i is the amount of fertilizer collected at point i in grams, \bar{x} is the average amount of fertilizer at all sampling points, and n is the number of sampling points. The CU value ranges from zero to one hundred, with values closer to one hundred indicating higher uniformity. In agricultural applications, a uniformity coefficient above eighty percent is considered acceptable.

The effective coverage area per oscillation cycle of the tube is calculated by considering the angular amplitude of the motion and the throw range. For oscillatory motion with a total angular amplitude θ_{total} from right to left and an average range R_{avg} , the approximate coverage area is:

$$A_{eff} = \frac{1}{2} R_{avg}^2 \theta_{total} \quad (23)$$

where θ_{total} must be in radians. For an oscillation amplitude of 135 to 140 degrees (2.36 to 2.44 radians) and an average range of four meters:

$$A_{eff} \approx \frac{1}{2} \times (4)^2 \times 2.40 \approx 19.2 \text{ m}^2 \quad (24)$$

The theoretical work capacity of the device, considering the operator's walking speed v_{op} , is calculated as follows:

$$C_{field} = A_{eff} \times v_{op} \times 3600 \text{ (m}^2/\text{hr)} \quad (25)$$

With a walking speed of 0.5 meters per second:

$$C_{field} = 19.2 \times 0.5 \times 3.6 = 34,560 \text{ m}^2/\text{hr} \approx 3.46 \text{ ha/hr} \quad (26)$$

Considering a field efficiency of about sixty to seventy percent due to stoppage time, refilling, and path adjustment, the effective work capacity is estimated at about two to two and a half hectares per hour.

2.6. Methodology of Experimental Tests

Field tests were conducted on the 5th of [Khordad 1390](#) (May 26, 2011) in paddy fields of [Galikash Golestan](#) county in IRAN province. Urea fertilizer weighing twelve kilograms, with a bulk density of 760 kilograms per cubic meter and an average particle diameter of two millimeters, was used as the test material. Operational parameters including vertical launch angle (thirty, forty-five, and sixty degrees), horizontal oscillation angle (one hundred twenty, one hundred thirty-five, and one hundred fifty degrees), and oscillation frequency (0.6, 0.77, and 0.9 Hz) were tested in three replications.

To measure the distribution pattern, circular collection containers with a diameter of twenty centimeters and a depth of ten centimeters were placed in a regular grid with half-meter intervals within a five-meter radius from the operator's point. For each parameter combination, the operator, carrying the device in a standing position and performing the oscillating motion of the launch tube, conducted the fertilizer spreading operation for thirty seconds. After each test, the amount of fertilizer in each container was weighed with a digital scale with an accuracy of 0.1 grams, and a two-dimensional distribution pattern was drawn. Evaluation parameters included effective range (the distance at which at least ten percent of the maximum fertilizer amount is deposited), Christiansen uniformity coefficient, application rate, and field efficiency.

To investigate the effect of launch tube length on exit velocity, three different lengths (eighty centimeters, one meter, and one meter twenty centimeters) were tested. The particle exit velocity was measured using a high-speed camera at a rate of one hundred and twenty frames per second and image analysis. Also, to evaluate the exit rate from the valve and compare it with the prediction of Beverloo's Law, valves with diameters of six, eight, and ten millimeters were tested, and the mass flow rate was measured by weighing the collected fertilizer in ten-second intervals.

3. Results and Discussion

Analysis of the experimental results showed that the designed system has satisfactory performance in fertilizer spreading, and the presented theoretical models predict the system's behavior with acceptable accuracy. The results are presented in four main sections, including evaluation of gravitational flow, analysis of kinetic energy transfer, investigation of the dispersion pattern, and comparison with existing systems.

Investigation of the exit rate from the valve for three different diameters and comparison with the prediction of Beverloo's Law showed that this law describes the flow behavior with good accuracy. For urea fertilizer with a bulk density of 760 kilograms per cubic meter and an average particle diameter of two millimeters, the Beverloo coefficients determined from fitting experimental data were $C = 0.58$ and $k = 1.92$. Table 1 shows the comparison of theoretical and experimental flow rates.

Table 1. Comparison of Theoretical and Experimental Flow Rates for Different Valve Diameters.

Orifice Diameter (mm)	Theoretical Flow Rate (g/s)	Experimental Flow Rate (g/s)	Relative Error (%)	Standard Deviation (g/s)
6.0	18.2	19.5	6.7	1.2
8.0	39.0	42.0	7.1	2.3
10.0	68.5	71.2	3.8	3.8

As evident from the table above, the relative error in all cases was less than eight percent, indicating the suitable accuracy of the Beverloo model for urea fertilizer. The increased error at smaller diameters is due to more complex flow effects at small scales and greater sensitivity to variations in particle properties. It was observed that until the hopper was completely empty, the flow rate remained almost constant, confirming independence from the material column height.

Experiments on the effect of launch tube length on particle exit velocity showed a direct relationship between these two parameters. By increasing the tube length from eighty centimeters to one meter twenty centimeters, the average exit velocity increased from 4.1 to 5.3 meters per second, showing an increase of about twenty-nine percent. This increase is due to the increased distance over which force is applied and thus the increased work done on the particles, which is consistent with the work-energy principle. Table 2 summarizes these results.

Table 2. Effect of Launch Tube Length on Particle Exit Velocity.

Tube Length (m)	Average Exit Velocity (m/s)	Kinetic Energy (mJ)*	Increase Relative to Baseline (%)
0.80	4.1 ± 0.3	8.4	Baseline
1.00	4.8 ± 0.4	11.5	17.1
1.20	5.3 ± 0.5	14.0	29.3

*For a particle with a mass of one milligram.

Investigation of the effect of operational parameters on the dispersion pattern and distribution uniformity showed that the launch angle and horizontal oscillation amplitude play a determining role. A launch angle of forty-five degrees provided the best combination of range and uniformity. At this angle, an effective range of four meters and a uniformity coefficient of seventy-eight percent were achieved. Smaller angles (thirty degrees) reduced the range to 3.2 meters but also reduced uniformity to seventy-two percent. Larger angles (sixty degrees) also reduced the range to 3.5 meters and achieved uniformity of seventy-four percent. These results are entirely consistent with projectile motion theory, which predicts maximum range at forty-five degrees.

Table 3. Effect of Launch Angle on Performance Parameters (Oscillation Angle 137.5 degrees and Frequency 0.77 Hz).

Launch Angle (°)	Effective Range (m)	Uniformity Coefficient (%)	Coverage Area (m²)	Maximum Height (m)
30	3.2 ± 0.2	72	15.8	0.58
45	4.0 ± 0.3	78	19.2	1.17
60	3.5 ± 0.3	74	17.4	1.47

The horizontal oscillation amplitude also had a significant effect on distribution uniformity. Oscillation of one hundred thirty-five to one hundred forty degrees created more uniform coverage compared to smaller or larger oscillations. Oscillation of one hundred twenty degrees caused the formation of high-density strips in the center and reduction at the edges, reducing the uniformity coefficient to sixty-five percent. Oscillation of one hundred fifty degrees also reduced uniformity to seventy-one percent due to increased oscillation speed and reduced particle deposition time at each point.

Table 4. Effect of Horizontal Oscillation Amplitude on Distribution Uniformity (Launch Angle 45 degrees and Frequency 0.77 Hz).

Oscillation Amplitude (°)	Uniformity Coefficient (%)	Effective Coverage Width (m)	Maximum to Minimum Ratio
120	65	3.8	3.2
137.5	78	4.6	1.8
150	71	5.1	2.4

The oscillation frequency also had a significant impact on distribution quality. A frequency of 0.77 Hz (period 1.3 seconds) provided the most optimal result. Lower frequencies (0.6 Hz) caused a striped pattern because particles had more time to settle at each position. Higher frequencies (0.9 Hz) also reduced the coverage area due to reduced effective acceleration and consequently reduced range.

Evaluation of the device's work capacity under field conditions showed that with a 20-liter hopper capacity (about fifteen kilograms of urea fertilizer) and an exit rate of forty-two grams per second, the continuous operation time is about three hundred and fifty-seven seconds (about six minutes). During this time, with a walking speed of 0.5 meters per second and a coverage area of 19.2 square meters, the theoretical work capacity is calculated as 3.46 hectares per hour. Field tests showed an effective work capacity of 1.5 hectares per hour, indicating a field efficiency of 43 percent.

Table 5. Comparison of Theoretical and Experimental Performance Parameters.

Performance Parameter	Theoretical Value	Experimental Value	Efficiency/Accuracy (%)
Work Capacity (ha/hr)	3.46	1.50	43.4

Fertilizer Application Rate (kg/ha)	300	315	95.0
Uniformity Coefficient CU (%)	-	78	-
Effective Range (m)	2.35	4.00	170*
Particle Exit Velocity (m/s)	4.80	4.80	100

*Increase due to secondary dispersion effect of the hose.

The reduction in experimental work capacity compared to the theoretical one is mainly due to non-productive times including hopper refilling, path adjustment, stopping at the end of rows, and initial acceleration. However, a work capacity of one and a half hectares per hour is significantly higher than traditional manual spreading (about 0.3 hectares per hour), indicating a fivefold improvement in productivity.

Comparison with existing commercial manual fertilizer spreaders shows that the proposed system has significant advantages. The Echo G-9 spreader, weighing 2.8 kilograms with a spinning disc mechanism, has a work capacity of 1.2 hectares per hour and a uniformity coefficient of sixty-five percent. The Scotts Handy Green model, weighing 1.8 kilograms, offers a work capacity of 0.8 hectares per hour. The designed system, weighing 0.9 kilograms, provides higher work capacity and better uniformity than both models.

Table 6. Comparison of the Designed System with Existing Commercial Fertilizer Spreaders.

Spreader Model	Weight (kg)	Capacity (L)	Work Capacity (ha/hr)	Uniformity (%)	Relative Price	Mechanism
Echo G-9	2.8	12	1.2	65	100	Spinning Disc
Scotts HG	1.8	8	0.8	70	75	Disc
Proposed System	0.9	20	1.5	78	40	Linear Tube
Traditional Manual	-	-	0.3	45	-	Hand

In addition to performance advantages, the proposed system is also superior economically. The estimated production cost is about forty percent of the Echo G-9 model, mainly due to the lack of need for a gearbox and complex mechanisms. The simple design also ensures easier maintenance and longer useful life.

4. Discussion and Conclusion

This research involved the design, construction, and comprehensive evaluation of an innovative manual fertilizer spreader that operates based on simple principles of classical physics, including gravitational flow and linear kinetic energy transfer. The results showed that this simple yet effective approach is capable of providing performance competitive with more complex systems. Theoretical modeling based on Beverloo's Law for gravitational flow and the work-energy principle for momentum transfer predicted the system's behavior with acceptable accuracy, with a relative error of less than ten percent observed in most cases.

Field tests under real conditions in paddy fields showed that the device, weighing less than one kilogram, is capable of spreading fertilizer over one and a half hectares per hour, which is five times the productivity of traditional manual spreading. The uniformity coefficient of seventy-eight percent achieved under optimal conditions falls within the acceptable range for agricultural applications and is comparable to more complex mechanized systems. This uniformity can lead to reduced fertilizer waste and improved input use efficiency, having positive economic and environmental impacts.

The optimal operational parameters included a launch angle of forty-five degrees, a horizontal oscillation amplitude of one hundred thirty-five to one hundred forty degrees, and an oscillation frequency of 0.77 Hz. These parameters provide an optimal combination of range, coverage area, and distribution uniformity. The sensitivity of the system's performance to these parameters indicates that proper operator training is essential to achieve optimal results. However, the acceptable parameter range is sufficiently wide to provide appropriate flexibility in use.

Key advantages of the designed system include simplicity of structure, ensuring easy maintenance and long useful life; no need for an external power source, enabling use in any condition; low weight, reducing operator fatigue; low production cost, facilitating widespread access; and the ability to control the distribution pattern, providing suitable uniformity. These features together provide high potential for widespread adoption among smallholder farmers, paddy fields, and mountainous regions.

The system's limitations must also be considered. Dependence on human force to create the oscillating motion of the launch tube can lead to fatigue in long-term applications, although the metabolic energy consumption is significantly less than traditional manual spreading. The limitation of throw range under strong wind conditions is also an operational challenge that can affect distribution uniformity. Additionally, the need to train the operator to achieve optimal uniformity and maintain suitable operational parameters is a practical requirement.

Future research can focus on several aspects. Optimization of the exit hose geometry using experimental design methods or computational fluid dynamics simulation can lead to increased uniformity and coverage area. Development of a semi-automatic flow rate control system that can adjust the exit rate based on the operator's walking speed can improve application uniformity across the field. Performance evaluation for a wider range of granular materials, including different types of fertilizers, seeds, lime, and other inputs, can expand the application scope.

Long-term studies to evaluate the durability and reliability of the system under real working conditions over several growing seasons are necessary. Also, a comprehensive ergonomic evaluation using standard methods and investigation of long-term effects on operator health can lead to design improvements. A comprehensive economic analysis including cost-benefit analysis, payback period, and comparison with alternative methods can help farmers make decisions about technology adoption.

This system, given its simplicity, efficiency, and cost-effectiveness, can play an important role in the development of small-scale agricultural mechanization and improvement of labor productivity in hand-cultivated farms. The application potential of this system extends beyond fertilizer spreading to areas such as seed sowing, lime application, micronutrient application, road salt spreading in winter, and distribution of other granular materials. Given the design innovation and suitable performance, this system has the potential for commercialization and patent registration, which could lead to the development of small rural industries and job creation.

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