PICKUP BEHAVIOR OF VEGETABLE SEEDS USING A VACUUM SEED-METERING UNIT (VSMU)
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سلوك التقاط بذور الخضروات باستخدام وحدة تلقيم البذور بالشفط

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ABSTRACT
This study aimed to evaluate the performance of a vacuum seed-metering unit (VSMU) developed for sowing vegetable seeds in trays under different vacuum pressures. Laboratory experiments were conducted using three seed types with markedly different physical and geometric properties: pepper, Armenian cucumber, and okra. Metering performance was evaluated in terms of the accuracy, miss, and multiple indices. The results showed that seed physical and geometric properties affected the optimal vacuum pressure, which was 1.52, 7.5, and 8.5 kPa for pepper, Armenian cucumber, and okra seeds, respectively. The corresponding accuracy indices were 93.54%, 91.25%, and 96.04%. Seeds with a relatively large mass, such as okra seeds, or low sphericity, such as Armenian cucumber seeds, required higher vacuum pressures than the flat, approximately circular pepper seeds. The developed VSMU therefore demonstrated its ability to handle seeds with diverse physical and geometric characteristics and achieve accurate seed metering.

الملخص
تهدف هذه الدراسة إلى تقييم وحدة شفط البذور المُصمَّمة لزراعة بذور الخضراوات بدقةٍ عالية، عند مستويات مختلفة من ضغط الشفط. تم إجراء التجارب المعملية على ثلاثة أصناف من البذور المختلفة في الخصائص الفيزيائية والهندسية: بذور الفلفل، القثاء الأرمني والبامية. تم تقييم الأداء باستخدام مؤشر جودة البذر، ومؤشر الفقد، ومؤشر المتعدد. وأظهرت النتائج أن الخصائص الفيزيائية للبذور تُؤثِّر بدرجة كبيرة على قيم ضغط الشفط المثلى، والتي بلغت 1.52، و7.5، و8.5 كيلو باسكال لبذور الفلفل، والقثاء الأرمني، والبامية على التوالي. وبلغت نسبة دقة البذر 93.54% و91.25% و96.04% على التوالي. تؤكد هذه النتائج أن البذور ذات الكتلة الكبيرة، كالبامية، أو ذات الكروية القليلة، كالقثاء الأرمني، تحتاج إلى ضغوط شفط أعلى مما تحتاجه بذور الفلفل الدائرية المُسطَّحة. وهكذا أظهرت وحدة الشفط المُطوَّرة القدرةَ على التعامل بدقة مع أشكال البذور المختلفة، وتطوير تقنيات الزراعة الدقيقة لمحاصيل الخضروات المتعددة.

INTRODUCTION
The Egyptian agricultural sector requires numerous physically demanding tasks and a large workforce. However, the sector faces several challenges: a shortage of skilled labor, high wages, and a lack of interest among young people in pursuing agricultural careers (*Abo-Habaga et al., 2024 a, b*). Meanwhile, vegetables are the most economical source of vitamins and minerals vital for a healthy lifestyle and are widely recognized as a fundamental element of food and nutrition security. To maintain an adequate supply of vegetables, further investment in agricultural output, post-harvest management, food safety, and market accessibility is necessary (*Zamuco et al., 2023*). Many agricultural operations, including sowing, transplanting, harvesting, and packaging, still require considerable manual labor. It leads to higher overall production costs (*Arteaga et al., 2020*). Sowing is the first critical operation in commercial vegetable seedling production. Depositing a single seed in each cell of a plug tray is essential because multiple seeds per cell result in excess seedlings, whereas missed seeds leave empty cells. These faults increase the labor required to add or remove seedlings later in the production process. Therefore, precision single-seed sowing is important for high-quality, efficient seedling production (*Xia et al., 2021*). Nevertheless, the overall mechanization level for vegetables is currently approximately 20%, much lower than that for food crops. Given the growing scale of vegetable cultivation, adopting mechanization for seeding is essential (*Li et al., 2025*). Sowing seeds is a crucial step after soil preparation. Among the many cultivation methods, tray planting is one of the most important, efficient, and reliable. This ensures increased productivity, uniform growth and seedling quality, and independent development of each seedling (*Lin and Lee, 2023*).

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However, manual sowing in trays is inaccurate and time-consuming, especially with small seeds, as one worker can sow 100 trays in 8 hours, producing approximately 9800 seedlings (*Gaikwad and Sirohi 2008*). It limits production accuracy and capacity due to fatigue and human error. Thus, solutions are moving towards the use of machinery for sowing, which can be complex at times due to variations in seed physical and geometrical properties (*Arteaga et al., 2020*). Tray planting systems require continuous preparation and filling of the soil before sowing. The seed placement process is crucial, as it directly affects the accuracy of placing seeds at the appropriate depth and location (*López et al., 2018*). Numerous machines and technologies were designed and developed for sowing, including mechanical and electrical components and intelligent robots, to improve plant production. Among these, pneumatic seeders have proven to be the most effective, enhancing plant uniformity and offering several other advantages (*Liu et al., 2024*; *Pradhan et al., 2024*). Several studies on vacuum seed meters emphasize the impact of the physical dimensions of the seed pick-up mechanism, including negative pressure, forward speed, and various operational variables, on measurement performance (*Liu et al., 2021*). *Karayel et al. (2004)* reported optimal suction levels for several vegetable seeds and emphasized the high accuracy of air suction in precision agriculture. Other research has discussed the mechanics of seed suction as a combination of differential pressure and pressure-gradient forces (*Shi et al., 2020*; *Li et al., 2021*). *Gaikwad and Sirohi (2008)* developed an inexpensive machine that pneumatically sows trays and found that suction pressure is the primary determinant of sowing accuracy, followed by nozzle diameter. Results under ideal seeding conditions were over 90% for both pepper and tomato seeds.

Similarly, *Li et al*. (2025) developed a precision seeding machine with a vacuum cylinder for irregularly shaped vegetable seeds. They applied computational fluid dynamics (CFD) modeling to study airflow distribution and the relationships among suction pressure, vibration frequency, and key seeding indices. *Ding et al*. (2024) developed a seed-planting machine for seedling trays and noted that seeds with different morphological characteristics require specific planting criteria. Failure to dynamically consider these criteria results in reduced accuracy and increased planting errors.

Zamuco et al. (2023) reported that the accuracy of their planting machine for seedling trays was significantly affected by pressure and seed surface area, with both factors strongly influencing machine performance. The vacuum seed-metering unit (VSMU) uses vacuum as its primary operating mechanism to achieve single, stable seed separation. Suction level is the primary operational factor affecting the efficiency of the capture and individualization process. The main purpose of this study is to evaluate the behavior of vegetable seed pick-up with various physical and geometric properties (pepper, Armenian cucumber, and okra) using a vacuum seed-metering unit (VSMU).

MATERIALS AND METHODS

The VSMU system (Fig. 1) was developed, and the research work was carried out at the AGRI-TRONICS laboratory, Department of Agricultural Engineering, Faculty of Agriculture, Mansoura University, Mansoura, Egypt, during the period January-May 2026.

The VSMU system

VSMU was developed for precision seed sowing, using a pneumatic mechanism that changes vacuum pressure based on seed physical and geometric parameters. The unit is composed of two basic components: the suction unit and the electrical control unit. The combination enabled precision single-seed pick-up with minimal seed misses and enhanced sowing accuracy across a range of seed types.

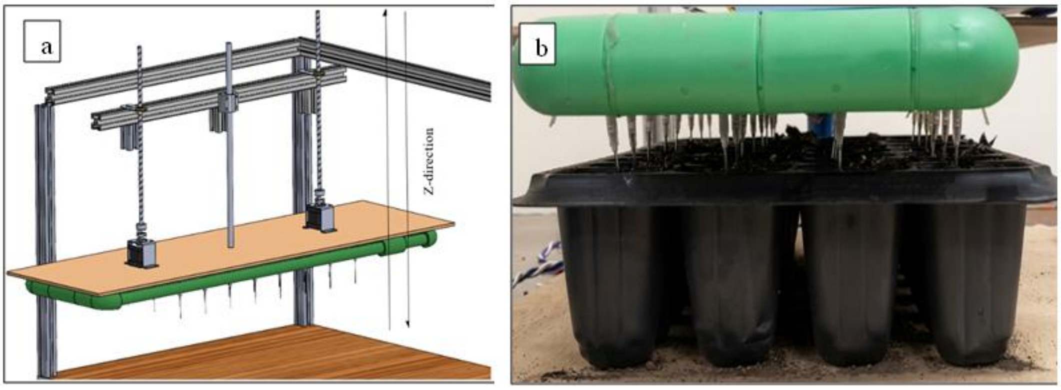

Fig. 1 – The VSMU system: (a) 3D design showing the direction of the z-axis, (b) photo of the VSMU during seed placement into the tray

Suction unit:

The suction unit picks up the seeds using needles with suction nozzles, driven by a suction motor connected to a flexible hose and PPR plastic pipes. The nozzle's picking surface was made flat by smoothing the needle's pointed nose to avoid seed damage, and its length was kept at 30 mm to facilitate picking seeds even as the seed level in the seed box declined (Fig. 2).

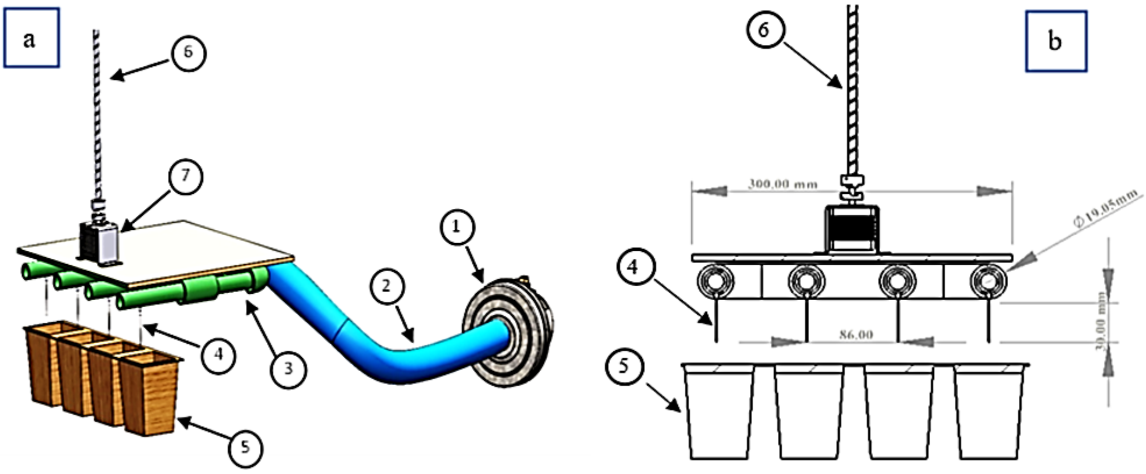

Fig. 2 – VSMU (a) Conceptual drawing and (b) Line diagram (Dim. in mm)

1 – Suction motor; 2 – Flexible vacuum hose; 3 – PPR plastic pipes; 4 – Nozzles; 5 – Seeds box; 6 – Lead Screw; 7 – Stepper motor

Seed box

A wooden seed box was designed measuring 550 × 270 mm with a depth of 30 mm, featuring cells with inward-inclined hive walls to centralize the seeds, thereby enhancing seed extraction during the unit's continuous operation.

Suction pipes and manifold

The VSMU's airflow system was designed using PPR plastic pipes of two different diameters. A 1-inch pipe was connected directly to the flexible hose supplying the suction motor, while 3/4-inch parallel pipes—matched to the cell arrangement in the tray—distributed airflow to the suction needles mounted on them.

Suction motor

A 2200 W suction motor, functioning at 220 V and 50 Hz, was incorporated to generate the pneumatic suction necessary for seed collection. This assembly facilitates the secure attachment of seeds from the seed box and prevents them from being ejected from the nozzle until they reach the tray.

Vacuum intensity adjustment mechanism

Servo motor

The SG90 servo motor served as a precise actuator, connecting the digital control system to the analogue AC dimmer. The servo was mechanically connected to the AC dimmer mechanism to adjust its displacement, enabling indirect control of suction strength via the user interface. It converted PWM control signals into accurate rotational velocities, enabling modulation of the suction operation level. The SG90 functions within a voltage range of 4.8 to 6.0 V. It provides a stall torque of 1.8 kg·cm (0.176 N·m) at 4.8 V and 2.0 to 2.2 kg·cm (0.196 to 0.215 N·m) at 6.0 V. It is compatible with PWM signals and possesses a rotational range of 0° to 180°. The no-load speed is approximately 0.12 seconds per 60 degrees.

AC dimmer

The SCR Voltage Regulator Module is a 2200 W, 220 VAC-type SCR control device for the smooth, continuous control of the effective voltage to the suction motor. It allows for accurate speed control of the suction motor to match the suction it produces. The SCR VC module phase angle controls AC for the SCR. Using phase-control technology, the SCR operates at an angle that reduces the effective load voltage relative to the RMS load voltage. The module simultaneously controls the motor's effective speed and the output voltage to the load, with no discrete switching. The module requires a 220VAC power source. It has a maximum capacity of 2200 Watts, making it suitable for controlling many high-wattage AC load motors, including Universal and AC motor types. The SCR VC module can be used as a VR for motor speed control and, in some applications, as a standard PID-compatible power modulation module. The SCR module's output voltage is modulated to provide adjustable suction, depending on system requirements, allowing precise control of suction pressure in the VSMU system to accommodate differences in seed properties. Based on initial experiments conducted on the studied seeds, the appropriate suction levels for sowing ranged from 1 to 9 kPa.

Operational pressures were measured at the flexible hose interface near the vacuum source using a calibrated pressure gauge. To guarantee experimental consistency and pressure stability, measurements were verified and stabilized before each trial run.

Seed release mechanism

After picking the seeds, the suction unit moves to the tray where the seeds will be placed, down into the soil. The needles penetrate the soil to a depth predetermined by the user, depending on the type of seed. When the specified depth is reached. Experimentally, the dimmer automatically pauses the suction motor for 10 seconds to ensure that the negative pressure is fully discharged, leaving the seeds for the needle nozzle. The suction unit then moves, leaving the seeds inside the soil.

Electrical and control components:

Arduino Mega

The Arduino Mega 2560 served as the principal microcontroller for system control and the integration of all electronic components. The system analyzed input signals from the user interface and sensors to produce control outputs that operated the servo motor and managed the AC voltage controller. It is predicated on the ATmega2560 microcontroller. It possesses a clock speed of 16 MHz. It functions at 5 volts. The device features 54 digital input/output pins, 15 of which support PWM output, 16 analogue input pins, and several serial communication interfaces, including 4 UARTs, facilitating simultaneous connections to multiple devices. The system comprises 256 KB of flash memory (8 KB allocated to the bootloader), 8 KB of SRAM, and 4 KB of EEPROM. The Mega 2560 was deemed suitable for overseeing the multi-component control architecture of the developed system owing to its superior I/O capacity and greater memory than smaller Arduino boards.

RAMPS 1.6 expansion control board

The RAMPS 1.6 extension control board was used to interface with and coordinate the system's motion-control components. It is based on a multi-axis control architecture using an Arduino-compatible shield. It supports up to 5 stepper motor drivers and modular connectors for end stops, heaters, and sensors and is normally run at 12–24 V DC. It has MOSFET power outputs for controlled loads and a heatsink assembly for optimized thermal dissipation at high current.

User interface – UI

The LCD2004 module was used as a human-machine interface (HMI) to monitor the system and select parameters. It consists of a 20 × 4-character LCD, an integrated rotary encoder, and an SD card interface. It runs on 5V direct current and communicates with the main controller over a standard parallel or I2C link. With this setup, the embedded firmware is in charge and can autonomously tune the system.

Power supply

A regulated 12 V DC switching-mode power supply (SMPS) powered the control and actuation subsystems. The SMPS accepts a wide input voltage range of 100-240 VAC, provides a stable 12 V DC output, and has a maximum current rating of 15 A, for a total rated output power of 180 W. The SMPS has built-in protections against overload, overvoltage, short circuits, and other hazards, helping extend its lifespan and ensuring normal operation with a wide variety of loads.

Stepper motor

The NEMA 17 stepper motor provides accurate positional control of the mechanical actuation components. The NEMA 17 stepper motor is a bipolar hybrid model with a standard step angle of 1.8° (200 steps per revolution). The electrical specification of the NEMA 17 stepper motor is a phase current rating of 1.2 to 2.0 A and a holding torque rating of 30-70 N·cm. The NEMA 17 stepper motor can be interfaced with drivers that use either pulse-width modulation (PWM) or step/direction control signals to provide accurate open-loop positioning. The general geometric specifications of the NEMA 17 stepper motor include a standard 42 × 42 mm frame size with a variety of different shaft combinations.

Stepper motor driver module

The DRV8825 driver was used to control the stepper motor, leveraging its high precision microstepping capabilities. In addition, the module provides a motor supply voltage range of 8.2 to 45 V and a maximum of 2.2 A per phase with sufficient thermal management. It supports microstepping resolutions up to 1/32 step, driven by STEP and DIR logic signals. Moreover, the driver includes built-in protection circuitry, including overcurrent, thermal shutdown, and under-voltage lockout (UVLO).

Studied factors

The developed VSMU was evaluated under various working conditions. The key elements assessed were seed morphology and vacuum intensity, as these factors directly affect seed pick-up efficiency and deposition accuracy.

1. Morphology: Three types of seeds were chosen to determine the performance of the metering unit for a variety of seed sizes, shapes, surface textures, and masses (Table 1): pepper *(Capsicum annuum L.)*, Armenian cucumber *(Cucumis melo var. flexuosus)*, and okra *(Abelmoschus esculentus L.)* seeds. For each type, length (L), width (W), and thickness (T) were measured on 30 seeds using a digital caliper (accuracy 0.01 mm), and thousand-seed mass (M) was determined with a digital balance. Sphericity (φ) and aspect ratio (R_a) were determined by Eqs. (1) and (2), according to *Mohsenin (1970).*

$$\phi = \frac{(L \times W \times T)^{1/3}}{L} \times 100 \tag{1}$$

$$R_a = \frac{W}{L} \times 100 \tag{2}$$

Table 1

The physical and geometrical properties of the studied seeds

Seed type	Parameter	L (mm)	W (mm)	T (mm)	φ (%)	Ra (%)	M (g/1000 seeds)
Pepper	Mean	3.71	3.87	0.89	62.96	104.31	3.5
	±SD	0.50	0.19	0.16			
	CV (%)	13.47	4.91	17.98			
Armenian cucumber	Mean	5.21	2.22	1.59	50.61	42.61	30.2
	±SD	0.60	0.22	0.49			
	CV (%)	11.52	9.91	30.82			
Okra	Mean	4.71	4.02	3.59	86.64	85.35	81.4
	±SD	0.30	0.24	0.36			
	CV (%)	6.37	5.97	10.02			

The data in Table 1 demonstrate significant differences in physical attributes among the three seed varieties evaluated. Okra seeds exhibited the largest dimensions (L = 4.71, W = 4.02, T = 3.59 mm), highest φ (86.64%) and R_a (85.35%), and greatest thousand-seed mass (81.4 g), suggesting a compact, near-spherical form. On the other hand, the Armenian cucumber seeds exhibited the largest elongation, the lowest φ (50.61%) and *Ra* (42.61%), and an intermediate thousand-seed mass of 30.2 g. The pepper seeds had a considerably low T of 0.89 mm, which resulted in a flat morphology, a moderate φ of 62.96%, and the smallest thousand-seed mass of 3.5 g. Such diversity in seed geometry and mass among the three varieties is likely to result in different pick-up reactions at varying suction pressures.

2. Vacuum pressure levels: The stability of pick-up and reliability of singulation were examined across different suction levels. The control system regulated the vacuum motor speed to generate the required pneumatic pressure, and the suction strength was electronically controlled. The experiment was performed at pressure levels ranging from 1 to 9 kPa.

Operation of the suction unit

Each seed type and suction pressure level had 15 trial replications for that specific combination. In each replication, 32 tray cells/nozzles were tested; therefore, the total sample size was 480 cells per treatment. The suction pressure was adjusted to the target value before each trial, allowed to stabilize, and verified with the vacuum gauge before beginning the seed pick-up cycle. After the user determines the required suction power variables, the suction unit moves to the seed box. The servo motor then automatically adjusts the dimmer to the specified suction level. At that time, the seeds are drawn toward the needle nozzle by the suction. Then the suction unit moves to the tray to be planted, and the seeds are placed inside the soil. The servo moves to close the suction motor for 10 seconds as a rest time to ensure all seeds fall and remain in the soil. Then, the suction unit returns to its position to start a new circuit, and the process repeats until the user-specified number of circuits is completed. The workflow procedure is shown in Fig. 3.

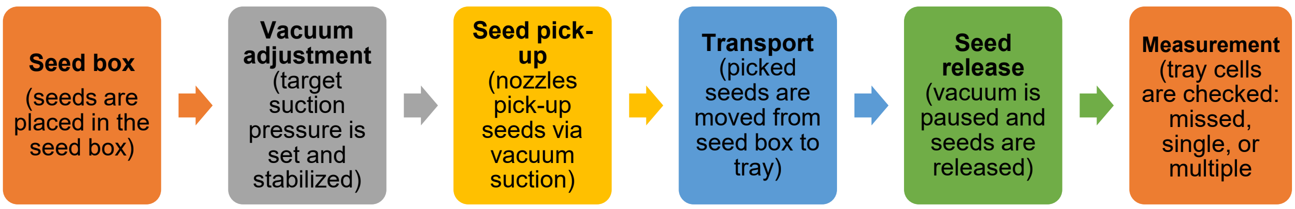

Fig. 3 – Workflow procedure of VSMU

Measurements

The total miss index (I_m), total multiple index (I_d), and accuracy percentage (S) were calculated according to Eqs. (3-5), respectively, according to *Kachman and Smith* (1995) and *Ismail et al. (2023).*

$$I_m = \frac{N_m}{N_t} \times 100 \quad (3)$$

$$I_d = \frac{N_d}{N_t} \times 100 \quad (4)$$

$$S = \frac{N_{success}}{N_t} \times 100 \quad (5)$$

where: S is the accuracy percentage, [%]; N_m is the number of cells that were "lost", and no seeds were sown; N_d is the number of cells in which "two seeds" (Doubles) descended; N_t is the total number of cells; $N_{success}$ is the number of successful cells.

Instruments:

1) A digital caliper was used to measure the seeds' dimensions. The digital caliper has a measurement range of 0 to 150 mm with an accuracy of 0.01 mm.
2) A digital balance was used to measure the mass of the seeds. It has a maximum capacity of 200 g with an accuracy of 0.001 g.
3) The vacuum pressure inside the system was measured by a vacuum gauge. The device's measuring range is -1 to 0 bar (0 to -30 inHg), and its accuracy class is 1.6 (±1.6% full scale).

RESULTS AND DISCUSSION

The VSMU system was evaluated using three parameters: the accuracy percentage index (S), the missing index (I_m), and the multiple index (I_d). In experimental trials, for each seed type, the S of vacuum seed placement was determined at different theoretical suction levels using these indicators. I_m shows a seed not captured due to insufficient suction pressure. I_d occurs when more than one seed is picked up at once, which can be caused by excessive vacuum pressure or by seeds clumping together around the nozzle. The accuracy index was calculated as the ratio of successful single-seed pickup events to the total number of pickup attempts, with both missed and multiple-seed pickups classified as unsuccessful events. Tests were conducted to determine the effects of different vacuum pressures on seed-pickup performance and singulation efficiency.

The experimental results were used to determine the optimal suction level for each seed type, defined as the level at which the accuracy percentage was maximized and the missing- and multiple-seed indices were minimized. For each seed type, 15 replications were conducted at each suction pressure level. The tested pressure levels ranged from 1 to 9 kPa (Figs. 4-7).

1. Pepper

Increasing the vacuum pressure from 1 to 9 kPa, the total miss index (I_m) changed slightly from 3% to 2%; the total multiple index (I_d) rose from 4% to 21%, while the accuracy percentage (S) decreased from 93% to 77%. As vacuum pressure increased, metering accuracy declined, mainly because (I_d) increased rather than (I_m) decreased (Fig. 4).

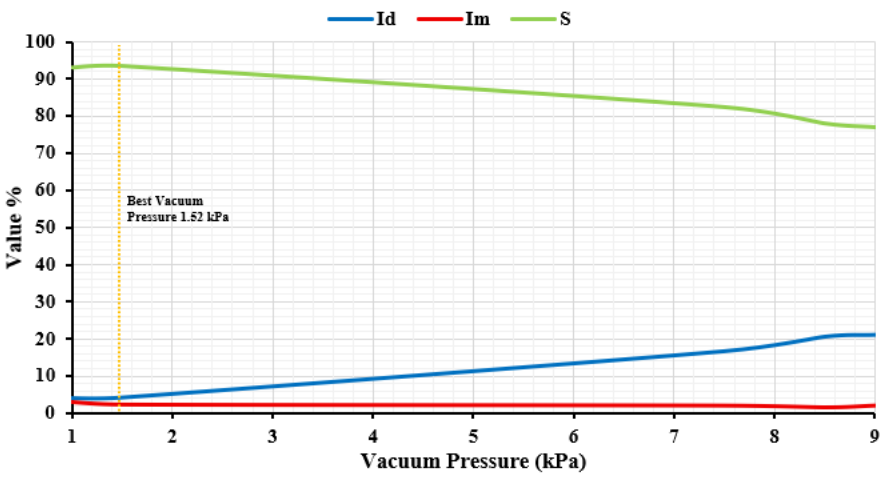

Fig. 4 – Effect of suction pressure on I_d, I_m, and S for pepper seeds

2. Armenian cucumber

Increasing vacuum pressure from 1 to 9 kPa, the total miss (I_m) index decreased from 14% to 2.3%; the total multiple index rose from 2% to 10.2%; and then the accuracy percentage (S) continued to rise from 84% to 91.25% at 7.5 kPa -Best Vacuum Pressure- and then decreased again to 87.5% at 9 kPa. As vacuum pressure increased, the reduction in the total miss index (I_m) was the dominant effect at lower pressures, while the rise in the total multiple index (I_d) became more pronounced at higher pressures (Fig. 5).

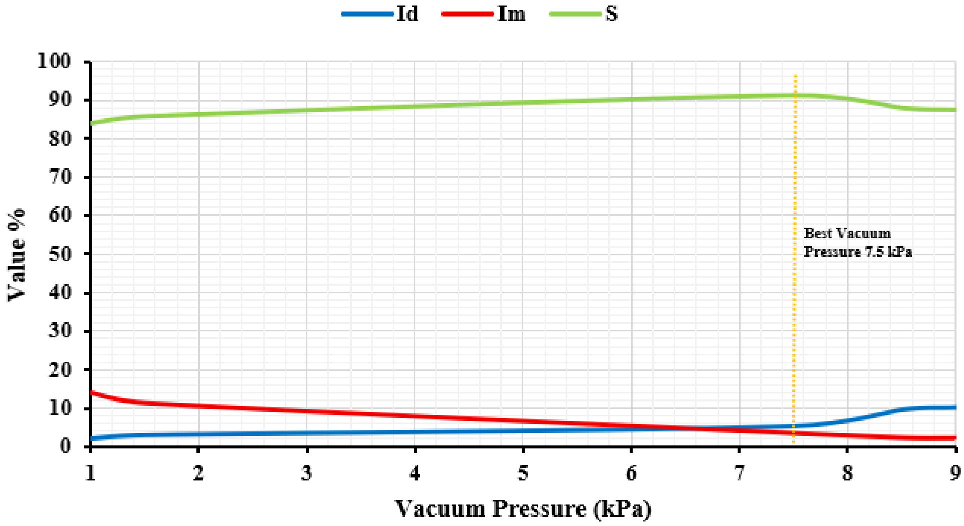

Fig. 5 – Effect of suction pressure on I_m, I_d, and S for Armenian cucumber seeds

3. Okra

Increasing vacuum pressure from 1 to 9 kPa, the total miss index (I_m) decreased from 15% to 2.4%; the total multiple index (I_d) rose from 0.1% to 2% and then the accuracy percentage (S) continued to rise from 84.9% to 96.04% at 8.5 kPa -Best Vacuum Pressure- and then decreased again to 95.6% at 9 kPa. As vacuum pressure increased, the reduction in the total miss index (I_m) was the dominant effect at lower pressures. In comparison, the rise in the total multiple index (I_d) became more pronounced at higher pressures (Fig. 6).

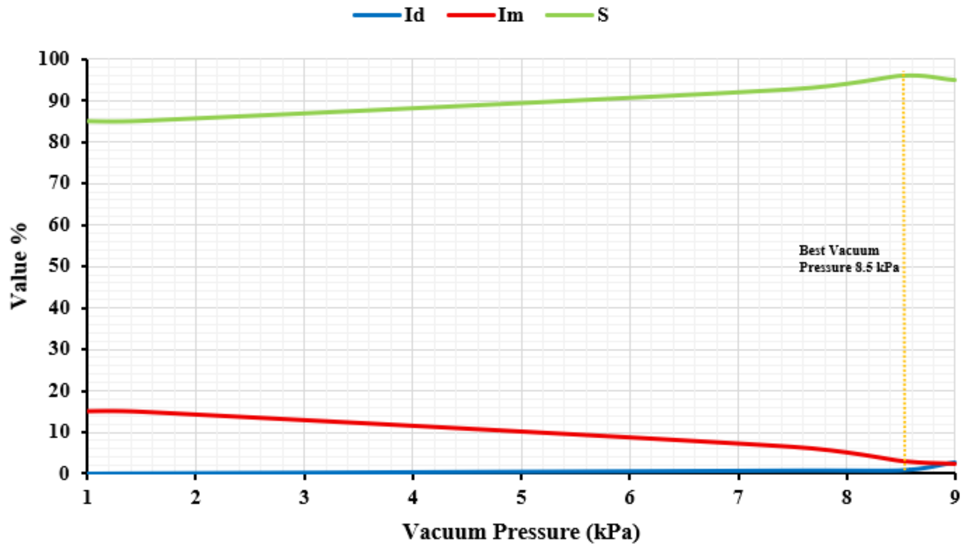

Fig. 6 – Effect of suction pressure on I_m, I_d, and S for *okra* seeds

Comparative seed singulation performance across crop types

The VSMU accuracy percentage varied across seed types at their respective optimum suction settings. For each crop, the best operating condition was selected based on the maximum accuracy percentage index (S) and minimum missing (I_m) and double (I_d) indices. The best suction pressures were 1.52, 7.5, and 8.5 kPa for pepper, Armenian cucumber, and okra seeds. Values of missing and multiple-seeds are expressed as mean ± standard deviation based on 15 replications. At the optimum suction pressures, pepper seeds at 1.52 kPa recorded 1.20 ± 1.01 missing events and 2.07 ± 1.22 multiple-seed events.

Armenian cucumber seeds at 7.5 kPa recorded 1.27 ± 0.70 missing events and 3.27 ± 1.03 multiple-seed events. Meanwhile, okra seeds at 8.5 kPa recorded 1.00 ± 0.65 missing events and 0.27 ± 0.46 multiple-seed events. These results indicate that the selected suction pressure for each seed type yielded stable seed pick-up performance, with acceptable variation across replications. The values obtained for *S*, I_m, and I_d for pepper seeds under these conditions were 93.54%, 2.29%, and 4.16%, respectively. Armenian cucumber seeds were recorded at 91.25%, 3.54%, and 5.2%, respectively. Okra seeds performed best overall with an *S* value of 96.04% and I_m and I_d values of 3.12% and 0.83%, respectively. The variation in singulation performance was attributed to differences in seed size, shape, and surface contact characteristics under pneumatic suction conditions.

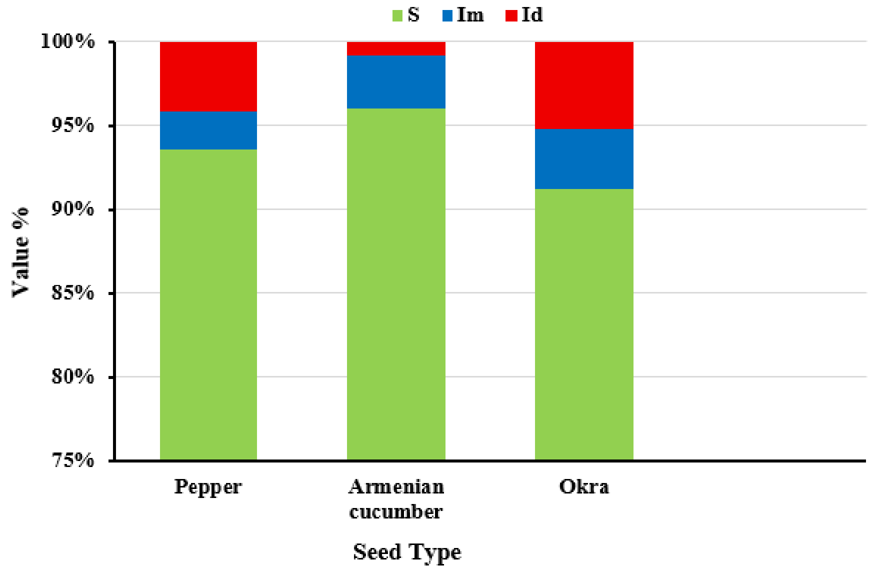

Fig. 7 – Seed singulation performance

Pepper seeds have a lower optimum vacuum pressure primarily because of their low seed weight and flat shape. This setup provides enough suction force to lift the pepper seeds at very low vacuum pressures. In contrast, the low sphericity and length of Armenian cucumber seeds would inhibit stable contact with the nozzle, thereby requiring higher vacuum levels to pick up the seeds reliably. Okra seeds, while highly spherical, have the highest seed weight and thus require more suction force to maintain stable attachment during transport than either of the other two seed types. Thus, the optimum vacuum pressure depends on the interaction between the seed's physical characteristics and the nozzle design, rather than on the seed's size alone. The results are in agreement with those of *Karayel et al.* (2022), determined in laboratory experiments conducted under controlled conditions, that the optimum vacuum pressure of the air-suction seed-metering device changed depending on the seed type and was 3.0 kPa for soybean, 4.0 kPa for maize, 2.5 kPa for melon and watermelon, 2.0 kPa for sugar beet, and 1.5 kPa for onion seeds. In the present investigation, a similar trend was observed, with pepper seeds requiring the lowest optimum vacuum pressure (1.52 kPa). This value closely matches that of onion seeds, due to their similar small seed size and reduced mass. In contrast, cucumber and okra seeds required much greater vacuum pressures, 7.5 kPa and 8.5 kPa, respectively. This trend is reconcilable with the higher vacuum pressure level observed for larger seeds such as melon, watermelon, soybean, and maize. This shows that the different morpho-physical properties of the seeds also determine the optimal vacuum pressure, with seed size and weight being the most significant factors. VSMU's success in providing accurate, repeatable seed singulation across all seed types confirmed prior theories that vacuum pressure depends on both seed type and the system employed. The findings that are used to assign optimum vacuum pressures (1.52 kPa for pepper, 7.5 kPa for Armenian cucumber and 8.5 kPa for okra) are consistent with previous research of pneumatic seeding systems in which small seeds typically require less suction (1.5-4.0 kPa) in controlled lab conditions (*Karayel et al., 2004*; *Karayel et al., 2022*). The findings are also similar to those for other small vegetable seeds, such as onion and sugar beet. The interaction between the physical properties of the seeds and the operational characteristics of the VSMU led to higher vacuum requirements for okra and Armenian cucumbers due to their irregular shapes and low sphericity. Because of these properties, the effective contact area between the seed and the suction area of the orifices is reduced; therefore, pick-up stability is reduced, which increases the amount of vacuum necessary to achieve proper seed singulation.

Higher suction demand during steady-state operation can result from operating modes and measured conditions that differ from those in the laboratory. Seed metering studies using vacuum systems have established that both seed characteristics and operational conditions can affect vacuum requirements, and that many observed deviations from ideal values can be attributed to seed–orifice interactions rather than to defects in the vacuum system (*Karayel et al., 2004; Jabir and Alfadil, 2022*). Therefore, it can be concluded that the optimal vacuum pressure arises from the interaction between the seed and the system, rather than being determined solely by the seed's characteristics.

CONCLUSIONS

The VSMU provided highly repeatable seed pick-up performance at a range of vacuum pressures and seed physical characteristics. Seed capture performance was influenced by vacuum pressure, as indicated by the single-seed pick-up accuracy percentage (S), miss index (I_m), and multiple index (I_d). The test results indicated that the vacuum pressure providing the best performance depends upon the seed characteristics, including seed shape/size, mass, and surface. The vacuum pressure at which the best pick-up performance for pepper seeds occurred was 1.52 kPa, corresponding to a single-seed pick-up (S) of 93.54%, a miss index of 2.29%, and a multiple index of 4.16%. The pick-up pressure for okra seed pick-up performance was 8.5 kPa, resulting in a single-seed pick-up accuracy percentage (S) of 96.04%, a miss index of 3.12%, and a multiple index of 0.83%. The pick-up performance for Armenian cucumber seeds was 7.5 kPa, yielding a single-seed pick-up accuracy percentage (S) of 91.25%, a miss index (I_m) of 3.54%, and a multiple index (I_d) of 5.20%. Overall, optimizing vacuum pressure improved single-seed capture efficiency and reduced missed and multiple-seed pick-ups, thereby minimizing erroneous seed placement by the vacuum pick-up system. Thus, the VSMU can be regarded as an efficient and versatile mechanism for precision sowing applications of seeds with different physical properties. Nevertheless, this study was conducted under controlled laboratory conditions and was limited to only three types of vegetable seeds. Future work should include other seed types and nozzles with different geometries, be tested across a wider range of operating conditions, and include nursery-scale validation.

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