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# Field Evaluation of a Pneumatic Prototype Machine Designed to Control the Colorado Potato Beetle in Potato Crops

[1, 2]Saad Almady and [1]Mohamed Khelifi

[1]*Department of Soils and Agri-Food Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada*
[2]*Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia*

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Corresponding Author:
Mohamed Khelifi
Department of Soils and Agri-Food Engineering, Université Laval, Quebec City, QC G1V 0A6, Canada
Email: mohamed.khelifi@fsaa.ulaval.ca

**Abstract:** The Colorado Potato Beetle (CPB), *Leptinotarsa decemlineata* Say, 1824, is a major insect pest of potato plants. It can greatly reduce potato yields if left uncontrolled. The most effective method of controlling the CPB is to apply chemical insecticides during its life cycle. However, the CPB tends to develop resistance to chemicals. Therefore, its control is difficult. This has prompted researchers to explore alternatives to insecticides. The use of pneumatic methods to control the CPB could considerably reduce the environmental impacts of insecticide applications and the need for farmers to handle toxic products. The objective of this study was to investigate the impact of a CPB pneumatic prototype machine on potato plant growth and tuber yield as well as its efficacy in controlling the CPB. Three airflow velocities (45, 50, and 55 m/s) and two travel speeds (5 and 6 km/h) were tested. The measured variables in organic and pneumatic control plots were CPB populations at different life stages, potato plant height, dry matter, Leaf Area Index (LAI), and tuber yield. The results indicated that the use of the pneumatic prototype machine to control the CPB had no significant negative impact on potato plant growth (height, dry matter, and LAI). Tuber yields were comparable to those obtained in the control plots and the prototype machine was highly effective in dislodging the CPB. These results confirm those obtained in 2018 and suggest that this innovative prototype pneumatic machine could efficiently control the CPB and significantly contribute to reducing the use of chemical insecticides.

**Keywords:** *Leptinotarsa decemlineata*, Potato, Pneumatic Control, Airflow Velocity, Travel Speed

## Introduction

The potato, *Solanum tuberosum L.*, is a staple food in many countries and the fourth most important crop after wheat, rice, and corn. According to the FAO (2020), 370,497,921 tons of potatoes are harvested annually. The Colorado Potato Beetle (CPB) (*Leptinotarsa decemlineata* Say, 1824; Coleoptera, Chrysomelidae) feeds on the leaves of the potato plant and is considered a significant herbivore pest (Hare, 1990; Alyokhin, 2009). This is mainly due to its appetite because a single CPB adult can consume 10 $cm^2$ of potato leaves per day and one larva can consume roughly 40 $cm^2$ of potato leaves over its entire larval stage (Ferro *et al*., 1985). The overuse of chemicals to control the CPB could lead to severe health and environmental problems (Alyokhin, 2009). Moreover, the CPB can develop resistance to almost all pesticides within 3.5 years (Hunt and Vernon, 2001). This insect pest is even more difficult to control because a CPB female can lay approximately 800 eggs over her lifetime (Harcourt, 1971). Furthermore, the CPB can adapt to severe weather conditions by hibernating. If left uncontrolled, it can consume 10 to 100% of potato foliage (Ferro *et al*., 1983) and reduce tuber yields by 30 to 91% (Senanayakei and Holliday, 1990).

To reduce the reliance on chemical insecticides, other methods for controlling the CPB have been explored. One possibility is the use of pneumatic control-that is, the use of positive or negative airflow to dislodge the CPBs. However, the CPBs must be efficiently dislodged without negative impacts on the potato plant's development and tuber yield. The behavior and gripping mode of the CPB play an important role in its resistance to airflow. When the beetles are under attack by a predator or when a plant, they are feeding on is shaken, they readily drop to the ground. At low temperatures, the larvae prefer to stay on the surface of the leaves to feed and rest, which probably increases their exposure to solar radiation (May, 1981). When the ambient temperature increases, they tend to move under the leaves (Lactin and Holliday, 1994). According to De Vries (1987), CPB can resist forces of 0.011 N when they are located on the upper surface of leaves and forces of 0.041 N when underneath or on the edges of leaves. Thus, the CPBs are prone to be easily dislodged when they are on the upper leaf surface. CPB adults can grasp objects using their tarsal claws (at the end of each leg), but the males have scoop-like hairs on the tarsal pads that enable them to grip slippery surfaces such as plastic and glass more easily than the females. The hairs also help the males to settle on females during mating (Pelletier and Smilowitz, 1987). However, Misener and Boiteau (1991) found that greater forces were required to remove CPB females than males from the lower surfaces and edges of leaves.

Many studies were conducted during the 1990s to explore the effect of airflow velocity on potato plant growth, the velocity, and orientation of airstreams required to dislodge CPB adults, and the airflow inside and around the hoods of pneumatic systems, as well as the effects of different combinations of airflow velocities, airflow widths and travel speeds on dislodging of CPBs (Khelifi *et al*., 1994, 1995a,b; 1996a,b; Lacasse, 1996; Lacasse *et al*., 1998a,b). Based on these findings, a four-row pneumatic prototype machine was designed and built at the Department of Soils and Agri-Food Engineering of Université Laval, Québec, Canada, and tested under real field conditions (Laguë *et al*., 1999). The prototype machine was operated at an airflow velocity of 50 m/s and a travel speed of 4 km/h; the power required for each unit was 4.1 kw. The results indicated that the pneumatic machine did not have any significant effect on the growth of potato plants. In addition, the tuber yields in plots subjected to the pneumatic machine and those treated with chemicals were comparable. The major drawback was the need to frequently stop to empty the collecting units, which reduced field capacity (ha/h).

In 2017, another pneumatic prototype machine was designed and built at the Department of Soils and Agri-Food Engineering of Université Laval to attempt to solve the issues related to the reduction in field capacity and the efficiency of insect dislodgment (Almady and Khelifi, 2021). This prototype machine was found to be effective in dislodging CPB larvae (Almady and Khelifi, 2021). However, its airflow velocity was limited to 38 m/s and the effect of the prototype machine on potato plants was not investigated because field testing occurred late in the summer. In 2018, several adjustments were made to the prototype machine to improve its airflow velocity, among other features (Almady and Khelifi, 2021). The objective of the present study was to further test this improved prototype machine in the field in the presence of more CPBs and investigate its impact on potato plant growth as well as its efficiency in controlling the CPB populations.

## Materials and Methods

### *Pneumatic Prototype Machine*

The four-row pneumatic prototype machine shown in Fig. 1 was described in detail by Almady and Khelifi (2021). It mainly consists of a centrifugal fan driven by the Power Takeoff (PTO) of the tractor. This centrifugal fan is connected to five plastic pipes, each ending with a blower unit. The CPBs settled on potato foliage are dislodged and transported by the air from the blower unit. The CPBs blown off the plants hit a mesh screen installed between plant rows and fall to the ground, where they are immediately crushed by a wheel installed behind each blower unit.

### *Field Trials*

Field trials were carried out at the Ferme Valupierre, Saint-Laurent-de-l'Île-d'Orléans, (46.8611°N, 71.0053°W), Québec, Canada. A complete randomized block design was used for the experiments in the field. The field was split into 28 experimental plots that were four rows wide and 6.5 m long (Fig. 2). The rows were spaced 0.86 m apart. The total area of each plot was 22.425 $m^2$ (0.0022425 ha). La Gabrielle de l'Île d'Orléans potatoes were seeded at 0.25-m intervals (i.e., 24 plants per row and 96 plants per plot). Four rows with 3.45-m buffer zones were installed around the plots to limit CPB migration. The total area of the experimental plots, excluding the buffer zones, was 627.9.68 $m^2$ (0.6279 ha).


**Fig. 1:** Overview of the prototype four-row pneumatic machine

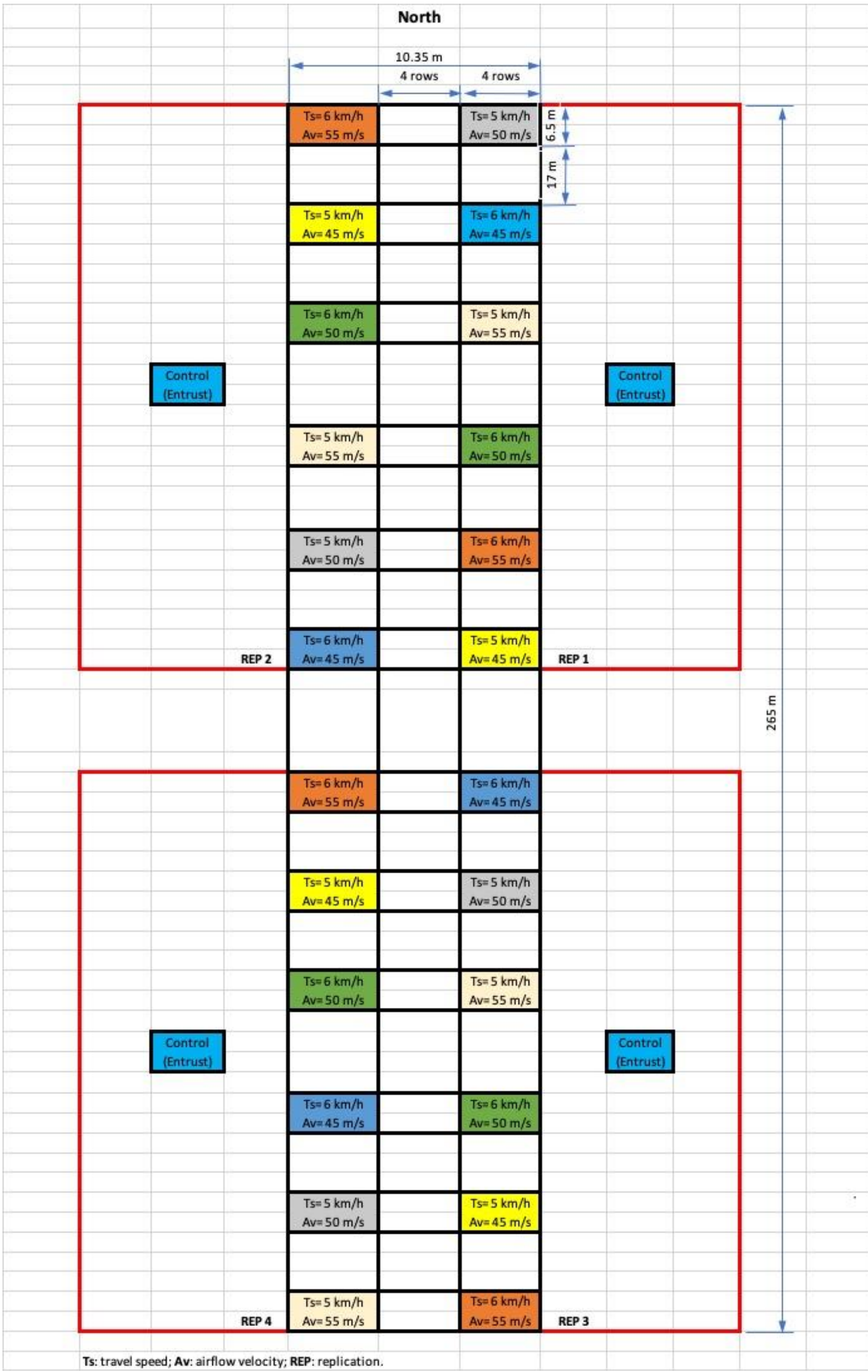


**Fig. 2:** Plot dimensions and the randomized arrangement of the treatments

The experimental design shown in Fig. 2 consisted of six treatments. The pneumatic prototype machine was operated at two travel speeds, 5 and 6 km/h, for each of the three blower-unit airflow velocities: 45, 50, and 55 m/s. The treatments were T1 (5 km/h and 45 m/s); T2 (5 km/h and 50 m/s); T3 (5 km/h and 55 m/s); T4 (6 km/h and 45 m/s); T5 (6 km/h and 50 m/s); and T6 (6 km/h and 55 m/s). The control (C) plot was treated with the biological pesticide Entrust. Each treatment, including the control, was replicated four times. In each plot, before and after treatment, the CPBs were counted on 10 plants chosen randomly. Three classes of CPBs were evaluated: Small larvae (L1-L2 stages); large larvae (L3-L4 stages); and adults. Dislodging efficacy was computed using the following equation:

$$Dislodging\ efficacy(\%) = \frac{number\ of\ CPBs\ before\ treatment - number\ of\ CPBs\ after\ treatment}{number\ of\ CPBs\ before\ treatment} \times 100$$

The pneumatic prototype machine was operated using a New Holland tractor (model TS115A, PTO 95 hp). Before and after the passage of the pneumatic machine, soil compaction was measured in the tractor path at one random location per plot (four times per treatment) using an electronic dial penetrometer (model PN-COMP-DIG-S-Digital Soil Compaction Meter, Turf-Tec International, USA). The airflow velocity was measured using a dynamic pressure anemometer (TA400, TROTEC, Heinsberg, Germany). The pneumatic prototype was used twice, on July 19 and August 23, 2019. To investigate the impact of the pneumatic prototype machine on the growth of potato plants, one representative stem per plot was cut weekly to measure its height and dry matter. The stems were dried at 55°C for 72 h in a forced-air oven so that their dry weight could be determined (Pelletier *et al*., 2010; ANSI/ASAE S358.3, 2012). In addition, the leaf area ($cm^2$) of three representative stems per plot was measured weekly using an automated infrared imaging system (LI-COR3100C Area Meter, LI-COR Inc., Lincoln, NE, USA), immediately after the samples arrived at the laboratory (Camargo *et al*., 2016). The Leaf Area Index (LAI) was computed using the following equation:

$$LAI = \frac{S \times N}{3 \times 10^4 \times A}$$

where, *S* was the leaf area of three stems from a plot ($cm^2$), N was the number of potato stems in the corresponding plot and A was the area of the corresponding plot ($m^2$).

Sampling began on July 19, 2019, and continued once per week for seven weeks until August 30, 2019. Tuber yields were determined at harvest for a 1-m section in the two central rows of each experimental plot. The harvest took place on September 11 and 12, 2019. The harvested potatoes were classified according to their diameter: 25 mm and less; 25 to 37.5 mm; and over 37.5 mm. Potatoes less than 25 mm in diameter were considered unsaleable and were not included in the evaluation of tuber yields. The yield was computed using the following equation:

$$Yield(kg / ha) = \frac{W \times 10000}{L \times S}$$

where, *W* was the weight of potatoes (kg), *L* was the length of the harvesting section (m) and *S* was the space between potato rows (m).

### Data Analysis

Outcome measures were compared between treatments using linear mixed models with a random effect of the block. Since a control treatment was added to the factorial design including travel speed and airflow velocity, two models were created for each outcome, except removal rate. The first model included treatment as a fixed effect with seven levels, including the control. The second had as fixed effects travel speed, airflow velocity, and their interaction, excluding the control treatment. For outcomes with repeated measurements, week and time of application were added as a fixed effect and heterogenous compound symmetry or a product of Unstructured with Compound Symmetry covariance structure was used. Results were considered statistically significant when the *p*-value was less than 5%. Bonferroni adjustment was used for multiple comparisons. All analyses were carried out with SAS Software, version 9.4 (SAS Institute Inc., Cary, NC).

## Results and Discussion

### Dislodging Efficacy of CPB L1 - L2 Larvae

The ANOVA results presented in Table 1 indicate that travel speed and airflow velocity did not have any significant effect on the dislodgment of the small larvae L1-L2 ($p = 0.1390$ and 0.1644, respectively). However, the interaction between travel speed and airflow velocity ($p = 0.0480$) as well as that between the time of passage of the prototype, travel speed, and airflow velocity ($p = 0.0334$) were significant.

Figure 3 shows that the average CPB dislodging efficacy at the L1–L2 stages following the first passage (P1) of the pneumatic prototype machine ranged between 79.8 and 85.5% for all treatments except for T6 using a travel speed of 6 km/h and an airflow velocity of 55 m/s (96.6%). The dislodging efficacy after the second passage (P2) of the pneumatic prototype varied between 83 and 100% for all treatments except for T6 and T2 (66.5 and 45.6%, respectively). This is mainly due to the very low population of L1–L2 larvae in some plots during the passage of the pneumatic prototype, which made it difficult to accurately evaluate dislodging efficacy.

Indeed, the population of CPB L1–L2 larvae varied between 58 and 336 on average per plot at the first passage of the pneumatic prototype and averaged 160 per 10 potato plants per plot. At the second passage of the pneumatic prototype, the population of L1-L2 larvae was very low and ranged between 0 and 21 per plot and the average per 10 potato plants per plot was only 3.70. Overall, the rate of removal of small larvae with the pneumatic prototype machine was particularly impressive.

### *Dislodging Efficacy of CPB L3-L4 Larvae*

The ANOVA results presented in Table 1 show that only travel speed and passage of the pneumatic prototype machine had a significant effect on the dislodging of L3-L4 larvae ($p = 0.0489$ and 0.0377, respectively). Dislodging efficacy was higher at the travel speed of 6 km/h than at 5 km/h (96% and 86%, respectively). It should be noted that the population of CPB L3-L4 larvae varied between 3 and 47 on average during the first passage of the pneumatic prototype and the average number of L3–L4 larvae per 10 potato plants per plot was 21.75. During the second passage of the pneumatic prototype, the number of L3-L4 larvae was overall very low (between 0 and 11 on average) and the average per 10 potato plants per plot was only 3.62.

### *Dislodging Efficacy of CPB Adults*

Dislodging efficacy was not affected either by travel speed ($p = 0.9799$) or by airflow velocity ($p = 0.6354$). The interaction between travel speed and airflow velocity as well as the passage of the pneumatic prototype machine was also not significant ($p = 0.6903$ and 0.7437, respectively). In both passages, the population of CPB adults was very low. This did allow an adequate evaluation of the rate of removal of CPB adults from potato foliage.

The observations made in the field indicated that the destruction of the CPBs falling on the ground between the rows using the wheels installed behind each blower unit was not successful. Therefore, additional weights on the tire frame are required to increase the pressure on the ground and eventually improve the efficacy of the destruction of CPBs.

### *Impact of the use of the Pneumatic Prototype Machine on the Height of Potato Plants*

The treatments had no significant effect on the height of plants ($p = 0.0857$). However, the effect on height over time (in weeks) was highly significant ($p<0.0001$) (Table 2).

Figure 4 shows the average height of potato plants by week (all treatments combined). Growth increased steadily in small increments during the first and second weeks and more sharply in the third week (by 46 mm) and by a comparable amount in the fourth week; it fluctuated from the fourth to the sixth week and then peaked in the seventh week at a height of 574.46 mm. This indicates that the pneumatic prototype machine, which was used on July 19, 2019 (the first week) and August 23, 2019 (the sixth week) did not negatively affect the growth of potato plants.

### *Impact of the use of the Pneumatic Prototype Machine on Dry Matter of Potato Plants*

The treatments did not have any significant effect on dry matter ($p = 0.8937$), although the average quantity of dry matter varied significantly over time ($p<0.0001$) (Table 2). There was the little dry matter at week 1 (11.40%). Thereafter, dry matter increased and then fluctuated between 12.77 and 13.2% (Fig. 5). Finally, it dropped to 11.79% in week 7 because the potatoes had matured.

### *Impact of the use of the Pneumatic Prototype Machine on the Leaf Area Index of Potato Plants*

Although there was a significant treatment effect on LAI at the 5% level in the global test ($p = 0.0416$) (Table 2), there were no significant differences between treatments with the Bonferroni method, which is a conservative test, especially for variables with a high number of categories. This indicates that the pneumatic prototype machine did not negatively affect the growth of potato plants.

The effect on LAI over time was highly significant ($p<0.0001$) (Table 2). However, the interaction between treatment and week was not significant ($p = 0.8898$). LAI was significantly affected by travel ($p = 0.0359$), whereas it was not significantly affected either by airflow velocity ($p = 0.8226$) or by the interaction between travel speed and airflow velocity ($p = 0.5412$). LAI was 1.1482 in treatments with a travel speed of 6 km/h and 0.9698 in treatments with a travel speed of 5 km/h because the plots with the pneumatic prototype traveling at 5 km/h had larger populations of CPBs.

At the beginning of week 1, the average LAI was 0.78 (Fig. 6). Subsequently, it increased rapidly, reaching a peak of 1.40 in week 6. Thereafter, it decreased to 1.34 in week 7, mainly because growth was focused on the root system to allow the potato tubers to mature.

### *Impact of the use of the Pneumatic Prototype Machine on Tuber Yield*

The ANOVA results presented in Table 2 indicate that the treatments did not have a significant effect on tuber yield ($p = 0.7160$). In the plots treated with the pneumatic prototype machine, tuber yield did not differ significantly between airflow velocities ($p = 0.9523$) and travel speeds ($p = 0.4259$). In addition, the interaction between travel speed and airflow velocity had no significant effect on tuber yield ($p = 0.3848$). The tuber yields in plots where the pneumatic prototype machine was used were comparable to those obtained in the control plots treated with the biopesticide Entrust. This result demonstrates that the pneumatic prototype machine is as efficient as Entrust at controlling CPB and is, therefore, an effective alternative to pesticides.

Overall, the rate of removal of L1-L2 larvae varied between 79.8 and 100%. This is particularly impressive in the presence of a high number of these small larvae, which are usually more difficult to dislodge from potato foliage, due to their small size, than L3-L4 larvae and adults.

Dry matter accumulation progressed normally during the growing season of potato plants. It was highest in week 4 and then decreased slightly until week 7. Dry matter accumulation was not affected by any of the treatments, including the control treatment.

The leaf area index increased rapidly until week 6 and then dropped in week 7. This agrees with Harris's (2012) observation that the leaf expansion rate increases gradually after leaf emergence and reaches its peak during the tuber bulking stage. This also confirms the LAI results from previous experimentation conducted in 2018 (Almady and Khelifi, 2021).

**Table 1:** Results of ANOVA of the comparison of dislodgment of Colorado potato beetles between L1–L2 and L3–L4 larval stages and adults

| Source of variation | L1–L2 | L3–L4 | Adults |
|---|---|---|---|
| Travel speed | 0.1390 NS | 0.0489* | 0.9799 NS |
| Airflow velocity | 0.1644 NS | 0.4025 NS | 0.6354 NS |
| Travel speed × airflow velocity | 0.0480* | 0.2196 NS | 0.6903 NS |
| Passage | 0.4991 NS | 0.0377* | 0.7437 NS |
| Passage × travel speed | 0.2812 NS | 0.1368 NS | 0.3317 NS |
| Passage × airflow velocity | 0.1705 NS | 0.2637 NS | 0.5911 NS |
| Passage × travel speed × airflow velocity | 0.0334* | 0.4744 NS | 0.7692 NS |

* = significant at the 0.05 level; NS = Not Significant

**Table 2:** Results of ANOVA of the effects of treatments on plant height, dry matter, Leaf Area Index (LAI), and yield

| Model | Source of variation | Height | Dry matter | LAI | Yield |
|---|---|---|---|---|---|
| Model 1: All treatments, including control | Treatments | 0.0857 NS | 0.8937 NS | 0.0416 § | 0.7160 NS |
| | Week | <0.0001* | <0.0001* | <0.0001* | ------- |
| | Treatments × Week | 0.2664 NS | 0.5887 NS | 0.8898 NS | ------- |
| Model 2: Factorial model with travel speed and Airflow velocity, without control | Travel speed | 0.0711 NS | 0.9540 NS | <0.0359* | 0.4259 NS |
| | Airflow velocity | 0.2653 NS | 0.7690 NS | 0.8226 NS | 0.9523 NS |
| | Travel speed × Airflow velocity | 0.0946 NS | 0.6015 NS | 0.5412 NS | 0.3848 NS |
| | Week | <0.0001* | < 0.0001* | <0.0001* | ------- |
| | Week × Travel speed | 0.5821 NS | 0.3195 NS | 0.6499 NS | ------- |
| | Week × Airflow velocity | 0.2489 NS | 0.9275 NS | 0.8747 NS | ------- |
| | Week × Travel speed × Airflow velocity | 0.2582 NS | 0.3682 NS | 0.6927 NS | ------- |

* = significant at the 0.05 level; NS = Not Significant
§ = not significant due to Bonferroni's method

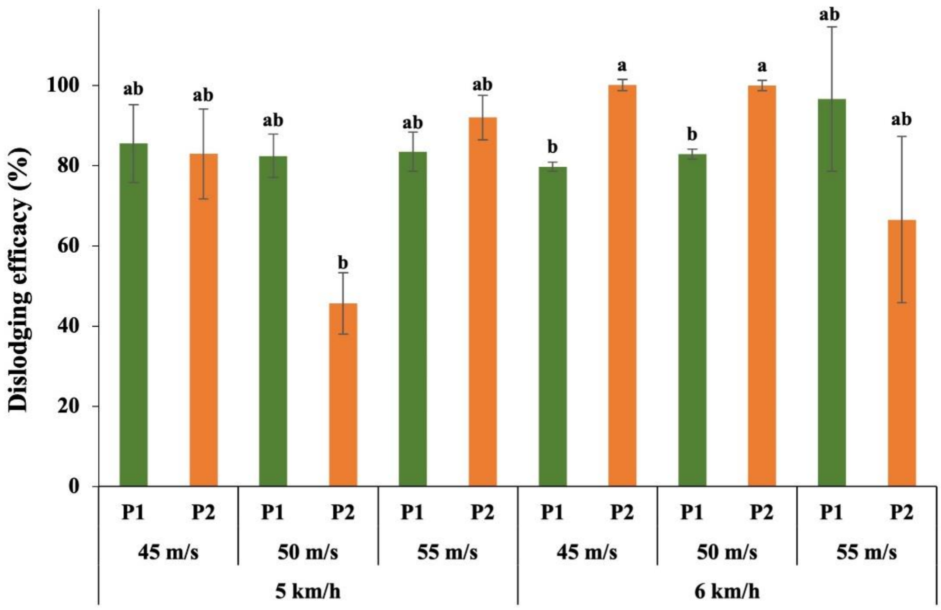


**Fig. 3:** Average dislodging efficacy of CPB L1-L2 larvae for all treatments after two passages (P1 and P2) of the pneumatic prototype machine at different airflow velocities and travel speeds. Vertical bars represent the standard error of the mean. Means with the same letter above the error bar are not significantly different at $p<0.05$ with the Bonferroni correction

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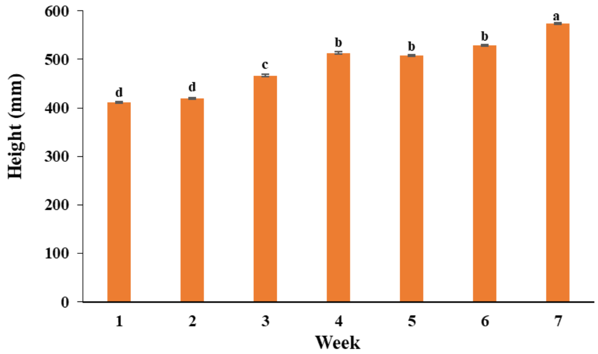


**Fig. 4:** The weekly growth of potato plants. Vertical bars represent the standard error of the mean. Means with the same letter above the error bar are not significantly different at $p<0.05$ with the Bonferroni correction

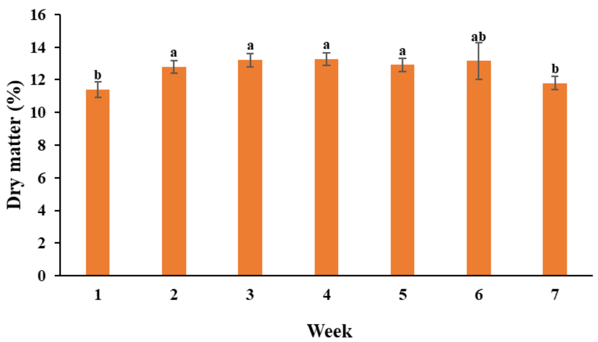


**Fig. 5:** Dry matter accumulation of potato plants over time under the experimental treatments. Vertical bars represent the standard error of the mean. Means with the same letter above the error bar are not significantly different at $p<0.05$ with the Bonferroni correction

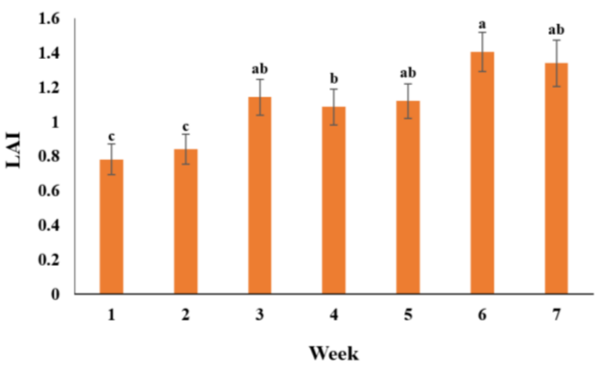


**Fig. 6:** Change in the Leaf Area Index (LAI) of potato plants over time under the experimental treatments. Vertical bars represent the standard error of the mean. Means with the same letter above the error bar are not significantly different at $p<0.05$ with the Bonferroni correction

Potato tuber yields obtained at the end of the growing season were comparable across treatments. This interesting result is another indicator that the pneumatic prototype machine is an efficient alternative to pesticides to control CPB populations in potato fields. It is also worth noting that the use of the pneumatic prototype machine did have any significant effect on soil compaction.

## Conclusion

The pneumatic prototype machine removed most of the CPB larvae at L1-L2 stages (90% or higher) at different combinations of travel speed and airflow velocity. In the case of stages L3-L4, the highest removal rate of 96% was obtained at a travel speed of 6 km/h. Overall, the highest rate of removal of L1-L2 and L3–L4 larvae was at a travel speed of 6 km/h and an airflow velocity of 45 m/s. Such a high travel speed is interesting as it allows increased field capacity (ha/h), whereas an airflow velocity as low as 45 m/s, compared to 50 and 55 m/s, is advantageous in terms of fuel consumption. The use of the pneumatic prototype machine to control the CPB did not have any negative impact on crop development as potato plant growth (height, dry matter, and LAI) and tuber yield was comparable to those obtained in the control plots. In addition, the pneumatic prototype machine did not cause soil compaction.

It is recommended to increase the tire pressure on the ground or integrate a new efficient system for adequate destruction of beetles fallen on the ground between rows of potato plants. Further tests should be carried out in the presence of a larger CPB population to test the improved prototype. This pneumatic prototype machine designed to control the CPB in potato fields is an interesting alternative to chemical insecticides.

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## Author's Contributions

**Saad Almady:** Conducted the experiments, collected and analyzed the data, interpreted the results, contributed to the writing of the manuscript.

**Mohamed Khelifi:** Designed the experiment plan, organized the study, made comments and suggestions throughout the laboratory and field experiments as well as the preparation of the manuscript.

## Ethics

This article is original and contains unpublished material. The corresponding author confirms that all authors have read and approved the manuscript and no ethical issues are involved.

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