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The Effect of Varying Compaction Levels on Soil Dynamic Properties and the Growth of Canola (*Brassica napus* L.)

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Abstract: Extremely low field emergence rates for canola are primarily attributed to soil compaction from field traffic during and after planting. This study aimed to determine the critical compaction level for canola emergence across different soil types. A laboratory experiment was conducted using sandy loam, silt clay, and clay soils, compacted to five levels (zero to four) using Proctor hammer drops after sowing canola (*Brassica napus* L.). The lab results were validated through two years of field experiments in sandy loam, applying four compaction levels (zero to three) using a tractor. Soil properties (bulk density and surface resistance) and canola growth parameters (plant emergence rate, count, height, and above-ground biomass) were measured. Zero compaction resulted in lower bulk density and surface resistance across all soil types. Laboratory results showed maximum emergence rates of 95% for sandy loam, 100% for silt clay, and 60% for clay, while field emergence rates were 63% and 87.59% in the first and second years, respectively, both at zero compaction. Recommendations include light or no compaction for sandy loam, and zero compaction for silt clay, while clay soil did not achieve the 80% emergence target at any compaction level. These results can assist agricultural producers in optimizing their seeding equipment setup and managing field traffic for canola production.

Keywords: soil; compaction; surface resistance; canola; emergence rate; biomass

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Citation: Owusu-Sekyere, E.; Chen, Y. The Effect of Varying Compaction Levels on Soil Dynamic Properties and the Growth of Canola (*Brassica napus* L.). *Agriculture* **2024**, *14*, 1976. https://doi.org/10.3390/agriculture14111976

Academic Editors: Mustafa Ucgul and Chung-Liang Chang

Received: 9 October 2024
Revised: 29 October 2024
Accepted: 2 November 2024
Published: 4 November 2024

1. Introduction

Canola (*Brassica napus* L.) is a commercially significant crop in the Canadian Prairies, with uses ranging from consumable oil to biofuels. Annual revenue doubled from CAD 15.4 billion to CAD 26.7 billion between 2007 and 2015 [1], driving an expansion of canola cultivation areas across Canada. However, emergence rates of canola as low as 50% have been reported [2]. This implies a 50% loss in revenue. Low emergence rates may reduce the yield and cause an economic loss due to the high cost of canola seeds. Factors contributing to low crop emergence rate include inadequate soil moisture, inappropriate seeding depth [3], seed variety and size [4], and soil compaction. Among these, soil compaction is considered a major cause [5]. High soil surface resistance of compacted soil prevents small seedlings from emerging [6]. Soil compaction also increases soil bulk density and surface resistance, which is detrimental to crop emergence and early growth of small seeds, like canola [5].

Soil structural properties significantly influenced by compaction include bulk density, surface resistance, and related characteristics [7]. These properties are associated with soil deformation resulting from induced stresses that vary according to the magnitude of the applied pressure [8] (such as tractor traffic) and other influencing factors [9]. Previous research has shown that an increase in soil bulk density and penetration resistance with the number of tractor passes is accompanied by a notable reduction in soil porosity [7]. Soil properties relevant to this study were bulk density and surface resistance, as compaction was found to notably increase both [10,11], with high values observed at high compaction levels.

The effects of soil compaction extend beyond changes in soil properties, impacting root and plant growth and reducing crop yield [12,13]. Varying conclusions regarding the effects of compaction on crop growth and yield have been reported from different academic studies. For example, Gelder et al. (2007) [14] reported no significant effect of traffic-induced compaction on corn yield and plant emergence. In contrast, other investigations have demonstrated a pronounced influence of compaction on crop growth and yield [7]. Ishaq et al. (2001) [15] documented subsoil compaction as a factor contributing to reduced grain and straw yield, diminished fertile tillers, and compromised water and nutrient use efficiency in wheat. Excessive soil compaction increases soil resistance to emerging seedlings and compromises root development, leading to poor crop performance [2,11,16]. The decrease in seedling emergence with an increase in soil compaction has been reported for many crops, such as corn [11], sorghum, wheat [10], and soybean [16]. A study performed by Buttery et al. (1998) [16] showed that a decrease in overall soybean and common bean growth was correlated with an increasing compaction level. The work conducted by Chan et al. (2006) [17] revealed a 34% reduction in yield and inhibited root growth in canola due to the compaction induced by tractor wheel traffic. These findings highlight the need for further research on how compaction affects soil properties and canola growth.

Existing studies have not specifically examined the effects of post-seeding soil compaction on the emergence of small seeds, such as canola, which are sensitive to soil resistance. Therefore, studying post-seeding compaction is crucial, as the results can guide the down pressure design of press wheels of seeders and the timing management of field traffic. The ideal soil compaction level favorable for canola emergence is currently unknown, making it essential to determine the compaction level that allows seedlings to emerge at an acceptable rate. Soil properties, such as surface resistance, vary with soil type and composition [16,18]. Therefore, it is important to include different soil types when investigating the effects of soil compaction levels on the emergence and growth of canola. Given that canola seeds are small relative to soil aggregates, controlled lab tests may help mitigate errors associated with highly non-homogeneous field soil conditions. However, to draw valid conclusions on the effect of compaction on soil properties and canola growth, field tests are necessary to confirm whether the lab results apply in real-world settings. This will be highly valuable to agricultural producers.

Therefore, the specific objectives of this study were (1) to evaluate in a laboratory the effect of different soil compaction levels on soil properties and canola (*Brassica napus* L.) emergence and growth under three distinct soil types, and (2) to validate the laboratory results of soil and plant responses in a field over two years. The results helped to determine the critical compaction level needed for achieving a target canola emergence rate for each soil type.

2. Materials and Methods

2.1. Laboratory Experiment

2.1.1. Description of Soil and Seed

The canola emergence test was first conducted under controlled laboratory conditions in 2020. The canola (*Brassica napus* L.) seed variety was Westar Canola, from a commercial seed supplier in Manitoba, Canada. Three soils, namely sandy loam, silt clay, and clay soils, were sourced from three different farms (Piney, the Ian N. Morrison research station at Carman, and a research station at the University of Manitoba Fort Garry campus, respectively) in southern Manitoba, Canada. The average moisture level for each soil type was adjusted to near its field capacity. Table 1 shows the compositions of these soils along with their gravimetric moisture content (d.b.), determined by oven-drying the soil samples for 24 h at 105 °C [19].

Table 1. Soil composition and gravimetric moisture contents for the laboratory experiment.

Soil Type	Clay (%)	Silt (%)	Sand (%)	Moisture Content (d.b.)%
Sandy Loam	14	16	70	24
Silt Clay	54	42	4	33
Clay	77	19	4	36

2.1.2. Laboratory Experimental Design and Test Procedure

The laboratory experiment used a completely randomized design. The treatments were five soil compaction levels: zero compaction level/no compaction ($C0_L$), compaction level one ($C1_L$), level two ($C2_L$), level three ($C3_L$), and level four ($C4_L$). The creation of these compaction levels is described below. Each treatment was replicated four times. Thus, 20 sample units (5 compaction levels $\times$ 4 replicates) were carried out for each soil type, totaling 60 tests for the 3 soil types in the experiment. The experimental design is illustrated in Figure 1a.

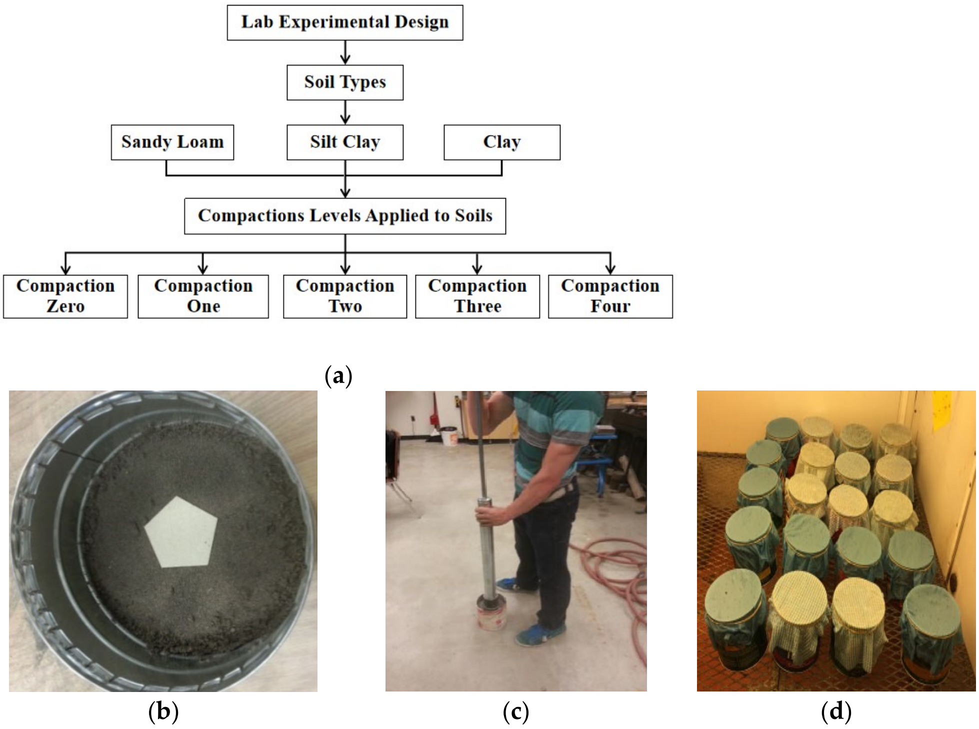

Figure 1. Laboratory experimental procedure: (**a**) flow chart of the experimental design, (**b**) seed positioning template, (**c**) soil compaction with a proctor, and (**d**) covered seeded containers in the environmental chamber.

For each soil type, 20 cylinders (166 mm in height and 154 mm in diameter) were employed as seeding containers and filled with soil up to a height of 20 mm below the container's rim. Subsequently, five canola seeds were positioned on the seedbed following a pentagon-shaped template as a guide, with one seed placed at each corner of the pentagon (Figure 1b). The distance between adjacent seeds was 30 mm. A predetermined amount of soil was then used to cover the seeds in each container, ensuring an appropriate depth of soil cover. This entire procedure, from soil preparation to seeding, was consistently applied across all the three soil types.

Following seeding, the 20 containers within each soil type were subdivided into 5 groups for compaction of the seed cover. A soil proctor (ASTM/Modified Proctor Compaction Rammer, ELE International, Loveland, CO, USA) with a hammer of mass 4.5 kg and a drop height of 0.457 m, was utilized for this purpose (Figure 1c). The group of containers, denoted by treatment $C0_L$, underwent no compaction. The remaining groups of containers received one, two, three, and four drops of the hammer of the proctor, corresponding to treatments $C1_L$, $C2_L$, $C3_L$, and $C4_L$, respectively. Given the hammer mass (m) of 4.5 kg, the gravitational acceleration (g), and the drop height (h) of 0.457 m, the values of compaction energy (potential energy = mgh) for the compaction levels $C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ were 0, 20.2, 40.4, 60.6, and 80.8 J, respectively. After seeding, the containers were transferred to an environmental chamber set at predetermined conditions of 19 °C, 10% RH, and an 8–16 h dark-photo-period (Figure 1d). To maintain soil moisture content, the containers were covered with wet clothes that were rewetted twice daily during the initial five days to mitigate soil water evaporation.

2.1.3. Laboratory Measurements

Soil compaction levels in the containers were quantified for bulk density and surface resistance. For this, separate containers of the same soil compaction levels as used in the seeding test were prepared without seeding. A Dail Pocket Penetrometer (Model: HM-502, Gilson Company Inc., OH 43035, USA) with a specified plunger surface area of 314 mm^2 was used to measure the surface resistance at three random locations in each container. For each container, a soil core was taken using a 50 × 50 mm cylindrical soil sampler. The gravimetric moisture content and soil dry bulk density were calculated after oven-drying at 105 °C for 24 h [19].

The number of plants that emerged in each container and the height of those plants were recorded daily for a total of 14 days after seeding. At the end of the 14 days, the plants were cut off at the soil surface, and their above-ground biomass was determined by oven-drying for 72 h at 60 °C [19].

2.2. Field Experiment

2.2.1. Description of the Study Site, Soil, and Seed

The field experiment was conducted during the summers of 2023 and 2024, from May to August. The experimental site was in Piney, Manitoba, Canada (49°07′15″ N, 96°07′56″ W). During the study months, the site recorded an average maximum temperature of 23.4 °C and a minimum of 10.5 °C, with 67% relative humidity, 0.8 mm/day of rainfall, and wind speeds averaging 13.31 km/h in 2023 [20]. For 2024, the site recorded an average maximum temperature of 21.9 °C and a minimum of 10 °C, with 74% relative humidity, 2.9 mm/day of rainfall, and wind speeds averaging 14.16 km/h [20]. The field had sandy loam soil with the same texture as that employed in the laboratory experiment, and the canola variety was also the same. At the time of measurements, the field soil moisture content was 19.67% and 35.58% (d.b.) for the first- and second-year tests, respectively.

2.2.2. Field Experimental Design and Test Procedure

In the field experiment, different compaction levels were created using tractor wheels on the field. The experiment was a completely random design with four compaction levels, namely zero compaction level/no compaction ($C0_F$), compaction level one ($C1_F$), level two ($C2_F$), and level three ($C3_F$), as treatments. Each treatment was randomly replicated 5 times, giving a total of 20 plots (4 compaction levels × 5 replications). The field plot layout is illustrated in Figure 2a.

Before compacting the soil, canola was seeded in the field using a disc seeder (4-row Plotter choice, Shelbyville, IN, USA). The seeding rate was 1 kg/ha and 3.8 kg/ha for the first- and second-year tests, respectively. As in the laboratory experiment, post-seeding compaction was applied to the soil by driving a tractor (John Deere 1023E tractor, weighing 656 kg, equipped with ballasts) at 2 km/h in the seeded field in the direction perpendicular to the seeding direction (Figure 2a). The tractor made one pass for the $C1_F$ treatment, two passes along the same track for the $C2_F$ treatment, and three passes along the same track for the $C3_F$, creating tracks (Figure 2b) for each compaction level.

On the wheel tracks, measurement areas were marked (Figure 2b) with each area measuring 1.8 × 0.22 m. The width of the measured area was the active tire width illustrated in Figure 2c. Six measurement areas were randomly selected in each plot, with three areas for soil property measurements and three areas for canola growth measurements. Additionally, in each plot, six random areas of the same dimensions (1.8 × 0.22 m), that did not have wheel tracks, were used for measurements of the zero compaction level ($C0_F$).

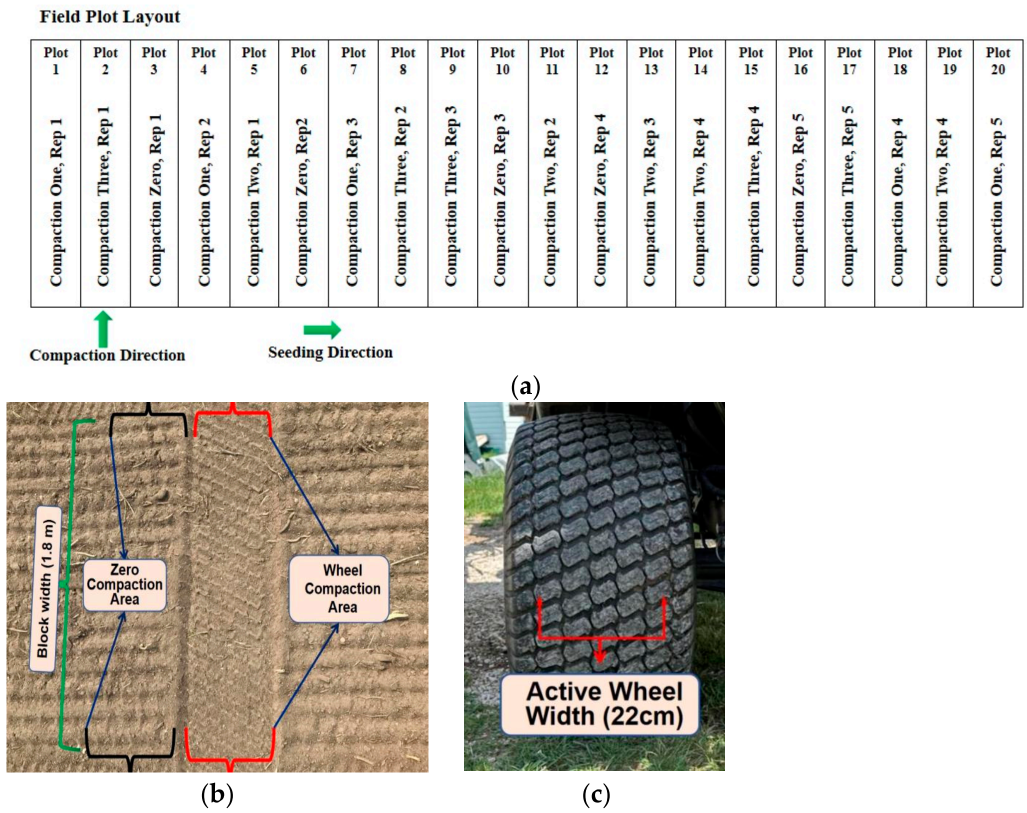

Figure 2. Field experimental process: (**a**) plot layout, (**b**) tractor wheel tracks showing compacted and non-compacted areas, and (**c**) active wheel width contributing to wheel tracks.

2.3. Field Measurements

As in the laboratory experiment, the soil compaction levels in the field were quantified for bulk density and surface resistance. Three soil cores (diameter 50 mm and height 100 mm) were taken from each measurement area per plot to measure bulk density. The soil surface resistance was measured using the same instrument as in the laboratory test at three measurement areas in each plot.

After 48 h of seeding, plant counting was conducted in the measurement areas of each plot every 48 h for five consecutive counts. After allowing the crops to fully emerge, a final count was conducted 27 days after seeding. Subsequently, the emergence rate was determined. Fully matured above-ground plants were collected from all plots three months post-seeding. The biomass of the plants was determined using the same oven-drying method performed in the laboratory experiment.

2.4. Data Analysis

One-way analysis of variance (ANOVA) was performed using R programming software version R4.2.2 and the 'car' package to analyze the effects of the treatments (soil compaction levels) on the measured parameters (soil properties and plant responses). The Tukey HSD test was utilized to determine the significant differences in the measured variables between all treatments at a confident level of 95%, using the same software.

3. Results

3.1. Soil Physical Properties

3.1.1. Bulk Density

In the laboratory test, the initial soil bulk density without compaction ($C0_L$) was the highest for the sandy loam soil (Figure 3a), followed by the silt clay (Figure 3b), and finally the clay soil (Figure 3c). The silt clay and clay soils had slight changes in magnitude, with no significant difference between $C3_L$ and $C4_L$ (Figure 3b,c). Similar results were reported by Li et al. (2016) [21]. However, the $C3_L$ of the sandy loam resulted in a lower bulk density than $C4_L$ (Figure 3a). Overall, soil bulk density was the highest for the sandy loam soil and lowest for the clay soil at all compaction levels. At compaction levels of $C2_L$ and lower, all the soils had a similar response to the compaction efforts, in terms of soil bulk density. The highest compaction in the sandy loam was 35.35% greater than in the silt clay and 59.05% greater than in the clay. Field soil bulk density results did not show significant differences between the compaction levels. In the first-year test, soil bulk density also increased when the compaction level was increased from $C0_F$ to $C2_F$, and there was no further increase in soil bulk density for $C3_F$ (Figure 3d). Although this trend was not statistically significant, it did not contradict the explained patterns in the lab experiment. However, the second-year test followed an increasing trend from $C0_F$ to $C3_F$ with small changes between compaction levels (Figure 3e). It registered lower bulk densities than the first-year test at all levels.

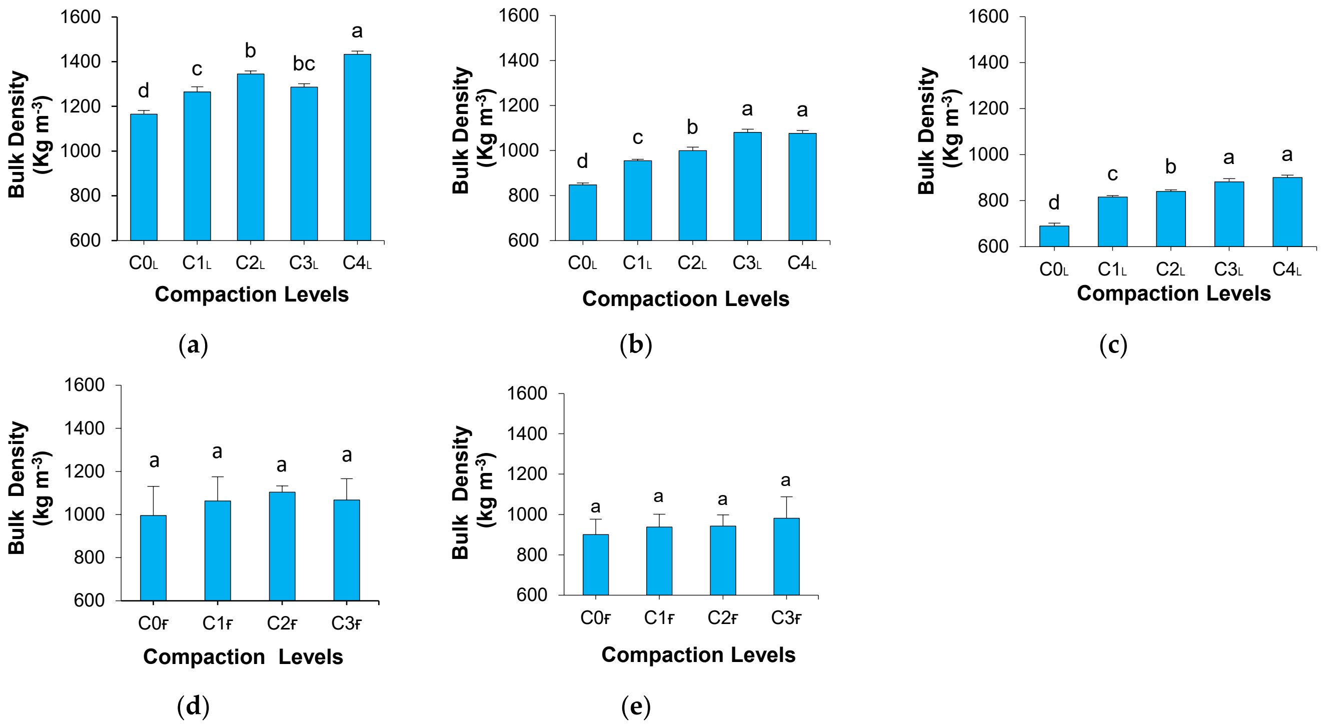

Figure 3. Bulk densities at varying compaction levels; (**a**–**c**) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively); (**d**,**e**) are field measurements of the sandy loam soil for first- and second-year tests, respectively ($C0_F$, $C1_F$, $C2_F$, and $C3_F$, represent compaction levels zero, one, two, and three, respectively). Means labeled with different letters in a graph were significantly different at $p < 0.05$.

3.1.2. Soil Surface Resistance

The laboratory test revealed an increasing trend in surface resistance with increasing compaction levels for all the three soil types (Figure 4a–c). All three soils had a very low resistance at $C0_L$. However, the rate of increase was different among the different soil types. When the compaction level was increased from $C0_L$ to $C3_L$, the soil resistance increased

29 times for the sandy loam soil (Figure 4a), 19 times for the silt clay soil (Figure 4b), and only 5 times for the clay soil (Figure 4c). For the sandy loam and silt clay soils, there was no further increase in resistance for $C4_L$. The change in the surface resistance of the clay soil between $C3_L$ and $C4_L$ was significant. Comparing the magnitudes of surface resistance at $C4_L$, the resistance of the sandy loam was 54% higher than that of silt clay, and 76% higher than that of clay.

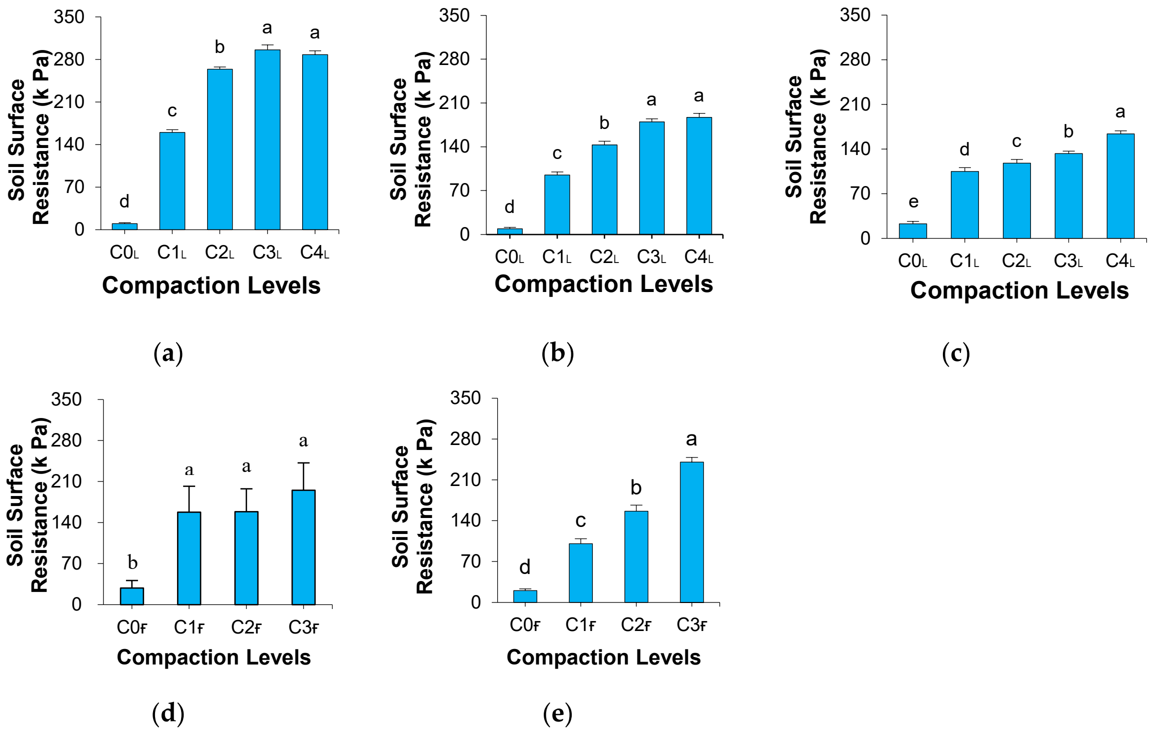

Figure 4. Soil surface resistances at varying compaction levels, where (**a**–**c**) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively); (**d**,**e**) are field measurements on the sandy loam soil for first- and second-year tests, respectively ($C0_F$, $C1_F$, $C2_F$, and $C3_F$ represent compaction levels zero, one, two, and three, respectively). Means labeled with different letters in a graph were significantly different at $p < 0.05$.

The first-year field test exhibited significantly lower soil surface resistance at the $C0_{F.}$ There were significant disparities between compaction levels zero and one (Figure 4d). However, the differences in soil resistance between $C1_F$, $C2_F$, and $C3_F$ were not statistically significant. Also, there was a general increasing trend of surface resistance with the soil compaction level (Figure 4d). This trend from the field was consistent with those obtained from the laboratory test [5]. However, the second-year test showed an increasing pattern with significant differences among all compaction levels (Figure 4e). This trend is consistent with the general trend in bulk density.

3.2. Plant Emergence and Growth

3.2.1. Qualitative Assessment of Canola Emergence

In the lab experiment, canola emergence and growth can be visualized from the photographs taken at the end of the two-week study (Figure 5a–c). These photos show 3 groups of 20 containers, with 1 group for each soil type. Within a group, the five containers in a row represent the five compaction levels ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$), while the four containers in a column represent the four replicates (R1, R2, R3, and R4) of the treatment. Three visual comparisons were made from these photos. Row-wise comparison within each group showed that better canola emergence was observed at a lower compaction level for all three soils. Column-wise comparison within each group showed that the four replications had consistent emergence, indicating low experimental errors. Comparison between the groups showed that the sandy loam soil had the worst plant growth, while clay soil had the best growth.

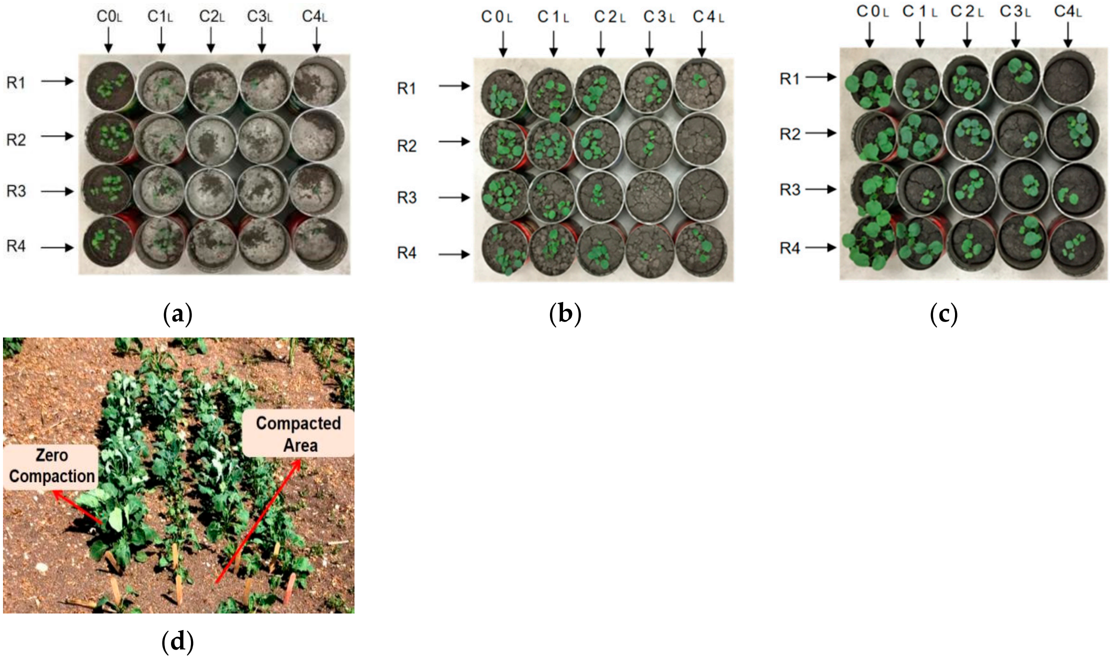

Figure 5. Canola emergence at varying compaction levels, where (**a**–**c**) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively; R1, R2, R3, and R4 represent replicates one, two, three, and four, respectively); (**d**) field results showing emerged canola plants at compacted and non-compacted sandy loam soil areas taken 27 days post-seeding.

Analogous results to those shown in the lab test were noticed in the field test for the same sandy loam soil (Figure 5a,d). Field plots on tractor wheel tracks (distinguished by popsicle sticks) exhibited a significant reduction in canola plants, while a greater number of plants were evident in the no compaction areas for same reasons as stated above.

3.2.2. Plant Count

In the lab test, the numbers of canola plants that emerged in each pot were counted daily over the entire observation period. The daily total number of plants of all the replicates are presented here. For the sandy loam soil, the first emergence was observed for $C0_L$. For this compaction level, canola seedlings started to emerge on the fifth day after seeding (Figure 6a). Increasing the compaction level to $C1_L$ resulted in a one-day delay in emergence. Further increase in compaction level to $C2_L$, $C3_L$, and $C4_L$ resulted in a delay by another day. At the early stages of observation, the two lower compaction levels ($C0_L$ and $C1_L$) demonstrated a steep increase in seedling emergence, and seedlings emerged over a 10-day period. There was no increase in plant count afterwards. The emergence rate for treatments $C2_L$, $C3_L$, and $C4_L$ increased much slower over time than the rates for the lower compaction levels, and then emergence ceased on the 8th day. At the end of the observation period, the plant count was reduced by 5% for $C0_L$, 20% for $C1_L$, 80% for $C2_L$ and $C4_L$, and 95% for $C3_L$.

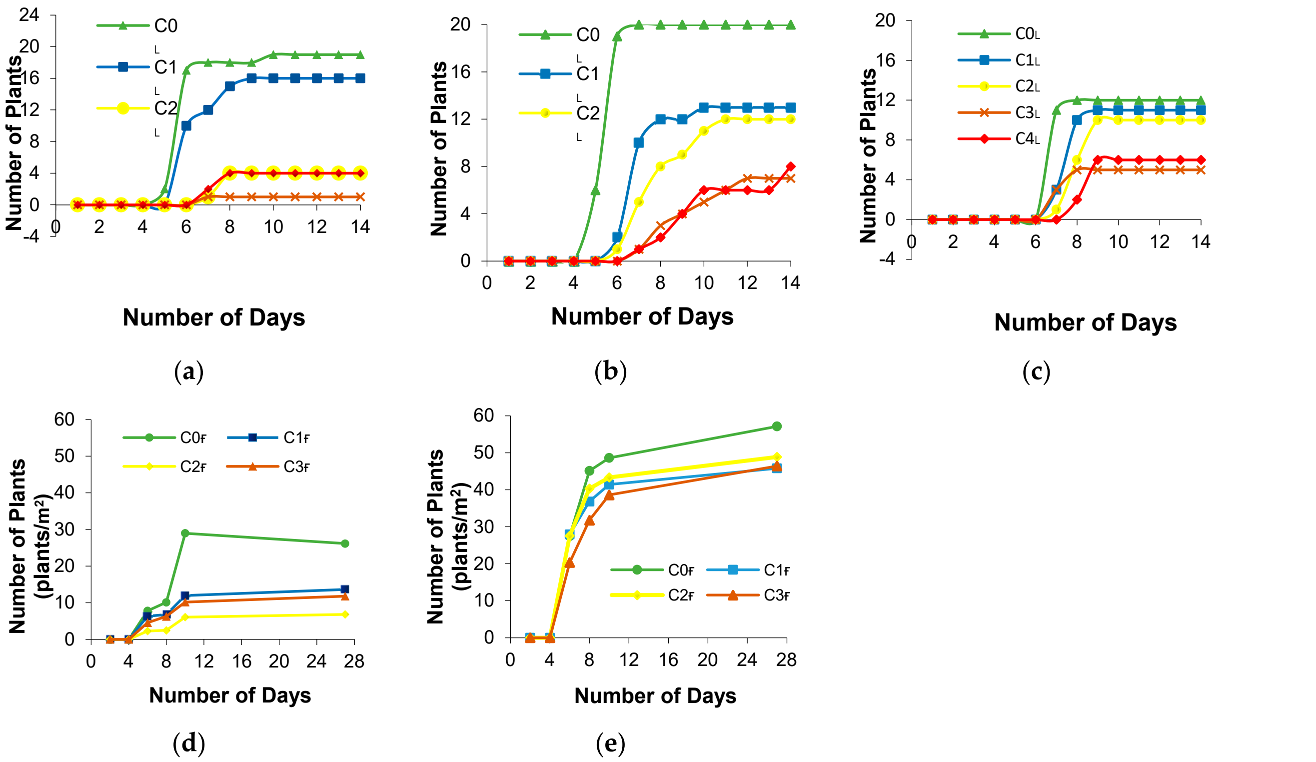

Figure 6. Plant population counts at varying compaction levels, where (**a**–**c**) are lab measurements for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively); (**d**,**e**) are field measurements using the sandy loam soil for first- and second-year tests, respectively ($C0_F$, $C1_F$, $C2_F$, and $C3_F$ represent compaction levels zero, one, two, and three, respectively).

For the silt clay soil, the first emergence was also observed on the fifth day, which was for $C0_L$, followed by $C1_L$ and $C2_L$ on the sixth day, and $C3_L$ and $C4_L$ on the seventh day (Figure 6b). The plants of $C3_L$ and $C4_L$ emerged until the end of the observation period. $C0_L$ had the highest plant count, with all the seedlings emerging by the seventh day. The plant count for $C1_L$ also demonstrated a rapid increase initially and slowly reached its maximum count of 12 plants on the 10th day. The count for $C2_L$ was lower, and new plants did not emerge after the 11th day. $C0_L$ had a 0% reduction in plant count, while the maximum reduction was 65% for $C3_L$.

For the clay soil, the first emergence for $C0_L$, $C1_L$, $C2_L$, and $C3_L$ occurred two days later than it did for the other two soil types and occurred on the eighth day for $C4_L$ (Figure 6c). No new seedlings emerged after 9 days of seeding for all the treatments. The number of plants was reduced by 40% for $C0_L$, with a maximum reduction of 75% for $C3_L$.

In the field test, canola emergence was assessed by the number of plants per unit field area over the observation period. Results from the two-year test showed that seedling emergence started six days after seeding for all compaction levels (Figure 6d,e). Both tests revealed a general increase in the number of emerging plants over time. A higher number of emerged plants were observed at the zero compaction level compared to the other compaction levels in both years. Towards the end of the twenty-seven-day period, a slight reduction in plant population was observed for $C0_F$ in the first-year test due to external environmental factors, such as nocturnal field grazing by deer. A higher number of plants were observed in the second year than the first year, due to the increased seeding rate in the second year.

3.2.3. Plant Emergence Rate

The emergence rate of the laboratory experiment was determined as the ratio of the total number of emerged plants to the total number of seeds sown. The results showed a decrease in seedling emergence rate with an increase in soil compaction level.

Emergence for the sandy loam soil showed two distinct groups of statistical differences (Figure 7a). The group with a high rate consisted of the $C0_L$ and $C1_L$ compaction levels, and the group with a much lower rate consisted of $C2_L$, $C3_L$, and $C4_L$. The average emergence rate for $C0_L$ was quite high (95%), while that for $C1_L$ was 80%. However, the average emergence rate for the latter groups averaged to 15%, much lower than the literature-reported range of 50–60% [22].

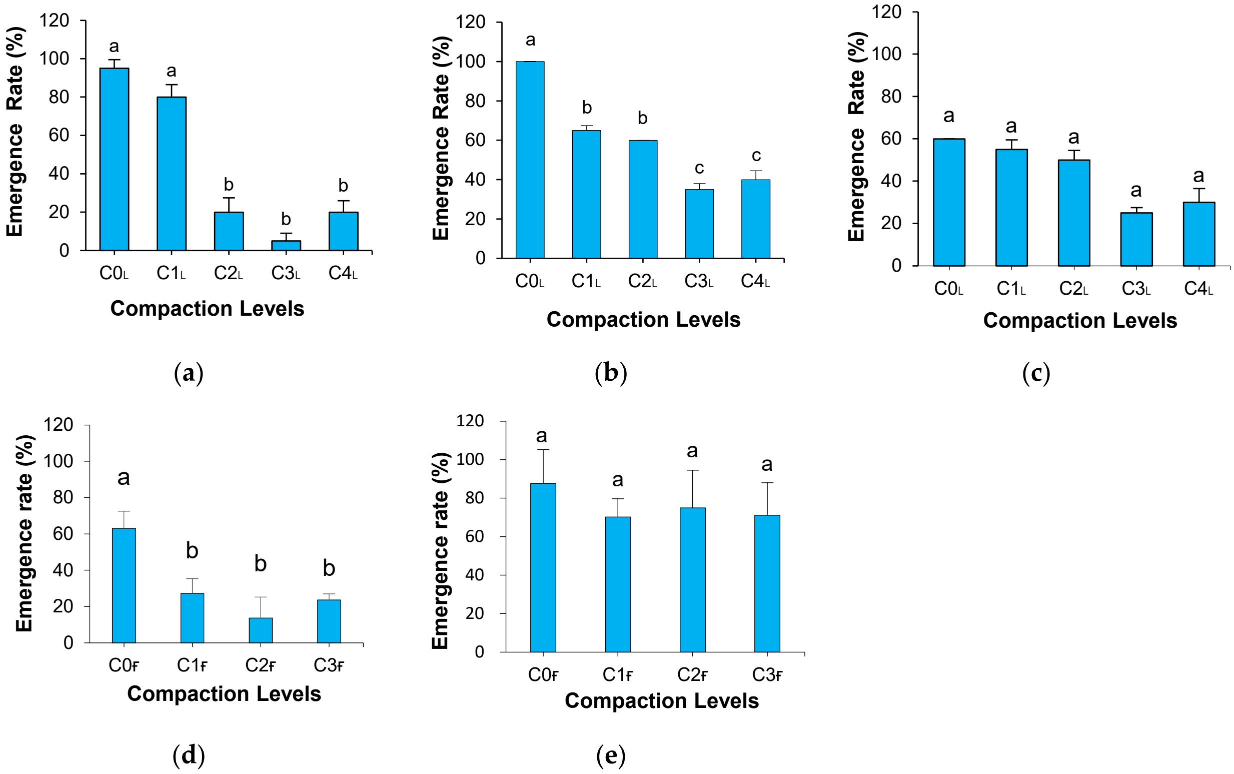

Figure 7. Canola emergence rate at varying compaction levels, where (**a**–**c**) are lab measurements taken for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively); (**d**,**e**) are field measurements on the sandy loam soil for first- and second-year tests, respectively ($C0_F$, $C1_F$, $C2_F$, and $C3_F$ represent compaction levels zero, one, two, and three, respectively). Means labeled with different letters in a graph were significantly different at $p < 0.05$.

The emergence rate of canola was also significantly different between compaction levels for the silt clay soil (Figure 7b). The emergence rate observed for the silt clay was 100% for $C0_L$, meaning that all seeds emerged when the soil was not compacted. The $C1_L$ and $C2_L$ treatments had 65 and 60% rates, respectively, which were significantly lower than $C0_L$. Very low emergence rates were observed in the higher compaction levels ($C3_L$, and $C4_L$).

The general trend of the clay soil was that compaction decreased the emergence rate. However, the trend was not statistically significant. None of the compaction levels had an emergence rate of 80% or higher (Figure 7c).

The emergence rate of the field test was determined as the ratio of the number of emerged plants to the total seeds sown per unit area, calculated using the known seeding rate and thousand kernel weight of canola. The results revealed a general trend of an inverse relationship between emergence rate and compaction level (Figure 7d,e). The seeding rate of 1 kg/m^2 used in the first-year test resulted in a much higher and significant change in magnitude between the zero compaction ($C0_F$) and the other compaction levels (Figure 7d). No significant differences were observed among compaction levels $C1_F$, $C2_F$, and $C3_F$.

Increasing the seeding rate in the second-year test to 3.8 kg/m^2 increased the emergence rate by 24% for $C0_F$, 42.97% for $C1_F$, 60.6% for $C2_F$, and 47.54% for $C3_F$ (Figure 7e). The 80% emergence rate was achieved only in the zero compaction level, which recorded a value of 87.59% (Figure 7e).

3.2.4. Plant Height

Plant height was measured in the lab condition, not in the field, since plant structure is not stable under weather conditions (wind and rain). In the lab experiment, an increasing trend was observed in the plant height with time, which lasted until the end of the observation period (Figure 8).

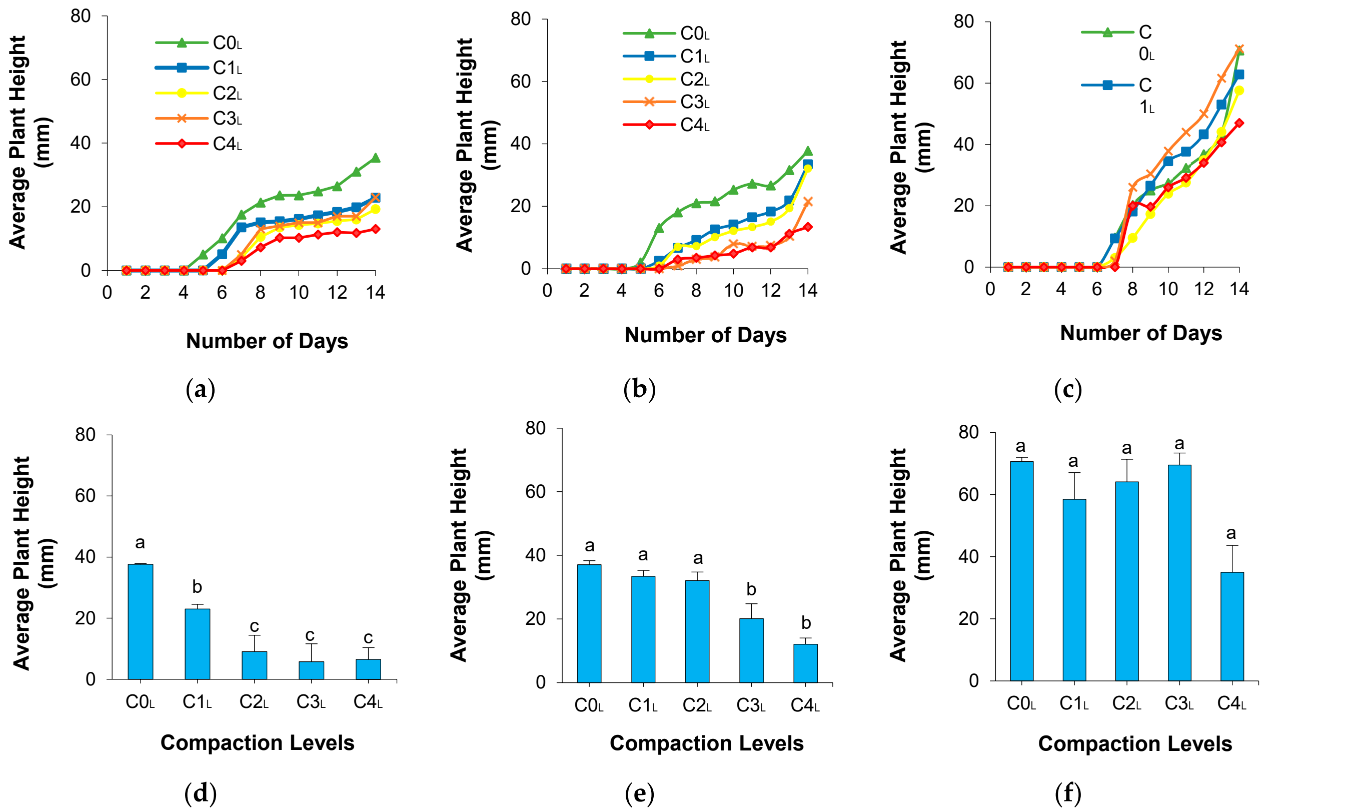

Figure 8. Lab measurement of plant height at varying compaction levels, where (**a**–**c**) are increasing values with time and (**d**–**f**) are average values. Both groups are for the sandy loam, silt clay, and clay soils, respectively. $C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively. Means labeled with different letters in a graph were significantly different at $p < 0.05$.

The initial growth rate for the sandy loam soil was similar for all the soil compaction levels, reflected by the similar slope of the plant height curves before the 12twelfth day (Figure 8a). Afterwards, there was a small increase in the plant height until the end of the observation period. However, higher heights were observed in the zero compaction level than the other compaction levels from the start of emergence until the end of the observation period. Very similar observation in plant height was observed between $C2_L$, $C3_L$, and $C4_L$.

Like the sandy loam soil, plant height data for the silt clay showed that the least compacted soil had a greater height at the initial growing stage (Figure 8b). Between the seventh and the twelfth day, plants at all compaction levels had a similar growth rate. The plant height experienced a rapid increase during the last two days. The $C3_L$ and $C4_L$ compaction levels had similar growth rates, as shown by the overlapped growth curves.

As compared with the other two soils, where the plant height increased gradually and non-linearly, the clay soil demonstrated a more rapid increase in plant height with a more linear increasing trend for the 14 days of growth (Figure 8c). Irrespective of the low plant count, the clay soil had higher plant height after the 14-day period.

To further demonstrate the effects of soil compaction on plant height, the data of the plant heights at the end of the observation period were averaged at each compaction level for each soil (Figure 8d–f). The sandy loam soil exhibited a decreasing trend in average plant height with increasing compaction level (Figure 8d). The maximum plant growth was observed at the non-compacted level, $C0_L$, with an average plant height of 37.7 cm. With slight compaction ($C1_L$), the average plant height reduced to 23.0 cm, a 39% reduction from $C0_L$. Additional compaction ($C2_L$) led to significantly lower plant heights. Subsequent compactions ($C3_L$ and $C4_L$) did not yield significant changes in average plant height.

In the silt clay soil, a similar average plant height to that observed in the sandy loam soil was seen for the $C0_L$ (Figure 8e). However, the change in magnitude between the compaction levels is less than that observed in the sandy loam soil. The zero compaction, $C0_L$, had the highest plant height, followed by $C1_L$ and $C2_L$ in that order, with no significant difference between the three levels. A significantly lower plant height was observed with additional compaction at $C3_L$ and $C4_L$. However, average plant height did not differ significantly between these two levels.

Compaction had no significant influence on the average height of canola plants within the clay soil (Figure 8f). The clay soil exhibited the highest plant height among all the three soils at all compaction levels. The plant emergence rate was notably less pronounced in the clay soil among all soils (Figure 7c). However, here, the clay soil had greater plant height than the other two soils.

3.2.5. Above-Ground Biomass

The sandy loam soil in the lab test showed biomass data exhibiting a similar trend to that of the plant height data. The highest biomass value was recorded for $C0_L$ (Figure 9a), which corresponded to the highest plant height. As the soil compaction level increased, significantly less biomass was produced. Biomass for the silt clay soil was much higher than the sandy loam soil and decreased with increasing compaction level (Figure 9b). The clay soil showed irregular trend with no significant difference in biomass with increasing compaction level (Figure 9c). The plant emergence data showed the worst performance in the clay soil, regardless of the soil compaction level. However, the overall amount of biomass was better than the sandy loam and as good as that of the silt clay.

In the field study, biomass was very sensitive to soil compaction in the first-year test (Figure 9d). A significant effect of compaction level on the biomass was observed. The decreasing trend of biomass with increasing compaction levels observed in both the first and second-year tests was similar between the field results (Figure 9d,e) and the lab results (Figure 9a), as the soil was sandy loam in both cases. However, compaction in the second-year test had no significant effect on biomass.

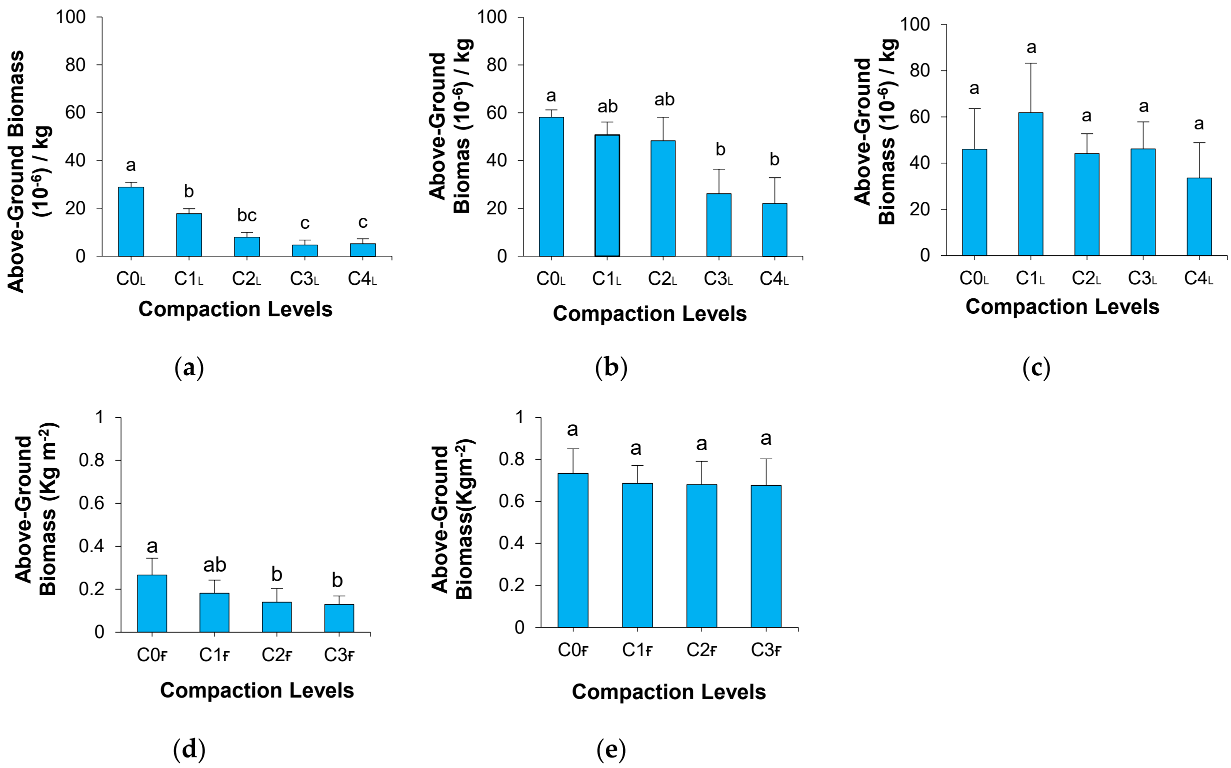

Figure 9. Canola above-ground biomass at varying soil compaction levels, where (**a**–**c**) are lab measurements taken 14 days post-seeding for the sandy loam, silt clay, and clay soils, respectively ($C0_L$, $C1_L$, $C2_L$, $C3_L$, and $C4_L$ represent compaction levels zero, one, two, three, and four, respectively); (**d**,**e**) are field measurements on the sandy loam soil for first- and second-year test taken 16 weeks post-seeding, respectively ($C0_F$, $C1_F$, $C2_F$, and $C3_F$, represent compaction levels zero, one, two, and three, respectively). Means labeled with different letters in a graph were significantly different at $p < 0.05$.

4. Discussion

The trend in bulk density observed in the lab test was expected, as sand particles have a higher density than silt clay and clay particles [23]. The observed increased trend in both the lab and field test was consistent with the findings of Phakdee and Suvanjumrat (2023) [24], who reported that soil compaction exhibits a positive linear relationship with soil bulk density. Lower compaction levels had less effect on soil porosity. Bulk density exhibits an inverse relationship with the porosity of soil samples of equal volume [25]. The lower values observed in the second-year test compared to the first year across all compaction levels may be due to differences in field locations, as there is no homogeneity among them (Figure 3d,e). The common lack of a further increase in soil bulk density beyond the third compaction level could likely be attributed to the limited number of soil pores which restrict further soil deformation under compaction [26].

The increase in compaction level caused a significant increase in surface resistance, as also recorded in the work carried out by Mileusnić et al. (2022) [27]. A similar trend in bulk density by soil type was translated into the trend in surface resistance, indicating that soil resistance was highly variable with soil type. The coarser the soil type, the higher its surface resistance, and vice versa [18]. Overall, different soils had different responses to the compaction efforts, in terms of soil resistance. The different behaviors of soil in response to compaction demonstrated the significance of investigating crop emergence and critical compaction levels for different soil types.

Higher soil bulk density and surface resistance were associated with a lower growth rate of canola [28,29]. Seedling emergence was delayed in clay soil due to large soil aggregates which impeded the upward movement of the canola cotyledons, as observed by

Vance et al. (2024) [30] in chickpea. As a result, some canola seeds were not able to emerge from the soil's surface. However, the clay soil's plant height was greater than sandy loam and silt clay. This observation might be due to the better water holding capacity of clay particles than sand particles in soil [31]. Comparable findings for sandy loam soil were observed in both the field and lab tests, as both used soil with the same composition. It was expected that plant count would reduce with the increasing compaction level from $C1_F$, to $C2_F$ and $C3_F$ for both tests, as observed by Kahlon et al. (2023) [32] for summer moon bean. However, the reverse was the case. Plant count decreased from $C1_F$ to $C3_F$ and then to $C2_F$ in the first-year test, and from $C2_F$ to $C3_F$, and then to $C1_F$ in the second-year test. This could be due to the heterogenous nature of field soils [33,34]. Similarly, this reverse phenomenon was also observed in the laboratory tests where the highest compaction level did not always result in the lowest number of emerged plants (Figure 6b,c).

High bulk density and surface resistance at high compaction levels adversely affected canola performance in terms of emergence rate. Specifically, the application of compaction pressure caused the reorganization of individual soil particles, leading to the closure of soil pores (reducing soil aeration), as discussed by Gong et al. (2022), Hess et al. (2019), and Otalvaro et al. (2016) [5,35,36], potentially impeding the upward movement of seedlings. This aligns with existing studies for different crops, such as corn [11], maize, sorghum, wheat [10], soybean [16], winter oilseed rape [37], and alfalfa [38]. The significantly low averaged emergence rate for sandy loam soil at $C2_L$ and $C3_L$ (Figure 7a) would significantly increase seed costs. Assuming a target emergence rate of 80%, only the $C0_L$ and $C1_L$ treatments were acceptable. Thus, the critical compaction level for the sandy loam soil is $C1_L$, which corresponded to a compaction energy of 20.2 J, bulk density of 1265 kg m^{-3}, and surface resistance of 160 k Pa. For silt clay, the only condition that had the emergence rate of 80% and greater was $C0_L$ (Figure 7b). Therefore, any form of compaction is unacceptable for seeding canola. Thus, its critical compaction level was $C0_L$, which corresponds to zero compaction energy, a soil bulk density of 848 kg m^{-3}, and a surface resistance of 9 k Pa. For clay soil, the highest emergence rate observed at $C0_L$ meant that at least 40% more seeds would need to be sown when growing canola crops in clay soil (Figure 7c). This would significantly increase production costs. The results implied that clay soil severely limited canola emergence, preventing it from reaching the 80% emergence rate, regardless of the compaction level. The reasons could be similar to those that affected plant count. The highest emergence rate of 63% in the first-year field condition was within the reported range in the literature [39], but it was far below the assumed target rate of 80% (Figure 7d). However, the second-year emergence rate (87.59%) increased beyond the target rate (Figure 7e).

For sandy loam and silt clay, the soil properties affected by compaction impacted the canola's above-ground biomass. Higher bulk densities and surface resistance of the soil resulted in significantly lower biomass (Figure 9). Compaction significantly reduced the canola emergence rate by 81.90% in sandy loam, 62.95% in silt clay and 45.70% in clay, consistent with studies of compaction effects on sugar cane [40], corn [41], and soybean [42]. Higher bulk density also influenced canola yield, causing a yield reduction, as noted in Gawęda and Haliniarz (2022) [43]. Future studies should include measurements of canola yields. These findings suggested that soil compaction from wheel traffic could be detrimental to soil health and plant growth in canola crop production.

5. Conclusions

The study highlights the need to minimize soil compaction to optimize canola emergence and growth. Lab and field tests revealed that higher compaction increased soil bulk density and surface resistance, which negatively affected canola performance, particularly in sandy loam soils. Silt clay soils showed similar sensitivity under lab conditions, while clay soil was largely unaffected by compaction. For sandy loam, no or slight compaction is recommended, and for silt clay, compaction should be avoided altogether. Clay soil did not meet the acceptable 80% emergence rate at any compaction level. In the field conditions, the target emergence rate of 80% was achieved only under no compaction treatment in one of the two studying years. Therefore, avoiding soil compaction is recommended regardless of soil type to optimize canola production. These findings provide practical guidance for agricultural producers in managing field traffic and modifying seeder equipment to prevent economic losses due to compaction-induced poor emergence. Future studies on additional soil types in field conditions, along with the application of these findings in designing and adjusting seeders, are recommended.

Author Contributions: Y.C.: Conceptualization, methodology, validation, resources, writing—review and editing, supervision, project administration, funding acquisition. E.O.-S.: Methodology, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Natural Sciences and Engineering Research Council of Canada (grant number: RGPIN-2019-05861).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: All relevant data are within the manuscript.

Acknowledgments: The authors thank all students who helped during the test the data collection.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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