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Physical Conditions That Limit Chickpea Root Growth and Emergence in Heavy-Textured Soil

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Abstract: The tillage method determines several soil physical parameters that affect the emergence of post-rice chickpea (*Cicer arietinum* L.) in the Indo-Gangetic Plain of South Asia. Mechanised row-sowing with minimum soil disturbance and crop residue retention in medium-to-heavy-textured soils will alter the seedbed when compared to that prepared after traditional full tillage and broadcast sowing. Whilst minimum soil disturbance and timely sowing may alleviate the soil water constraint to crop establishment, other soil physical properties such as soil strength, bulk density, and aggregate size may still inhibit seedling emergence and root elongation. This study's objective was to determine the limitations to chickpea crop establishment with increasing bulk density and soil strength, and different aggregate sizes below and above the seed. In two growth cabinet studies, chickpea seed was sown in clay soil with (i) a bulk density range of 1.3–1.9 Mg m^{-3} (Experiment 1) and (ii) the combination of bulk densities (1.3 and 1.8 Mg m^{-3}) and aggregate sizes (<2 mm and >4 mm) above and below the seed (Experiment 2). Root length was significantly reduced with increasing bulk density (>1.4 Mg m^{-3}), and soil strength impeded early root growth at >1 MPa. Where main root growth was impeded due to high bulk density and soil strength, a greater proportion of total root growth was associated with the elongation of lateral roots. The present study suggests that the soil above the seed needs to be loosely compacted (<1.3 Mg m^{-3}) for seedling emergence to occur. Further research is needed to determine the size of the soil aggregates, which optimise germination and emergence. We conclude that soil strength values typical of field conditions in the Indo-Gangetic Plain at sowing will impede the root growth of chickpea seedlings. This effect can be minimised by changing tillage operations to produce seedbed conditions that are within the limiting thresholds of bulk density and soil strength.

Keywords: aggregate size; bulk density; desi chickpea; minimum tillage; soil strength; *Cicer arietinum* L.; germination

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1. Introduction

In rice-based cropping systems of the Indo-Gangetic Plain of South Asia, chickpea (*Cicer arietinum* L.) crops are grown post-rice in the winter (rabi) season. In 2021, 15 million t of chickpea grain was produced on 15.8 million ha, with 76% produced in India [1]. In small-holder farms, chickpea can be grown as an additional crop in the year: if sold, it may alleviate poverty; if consumed, it can provide an additional protein source, which may improve nutrition for farming families [2].

Under the current sowing techniques used (broadcasting seed following two to five passes of full tillage [3]), the soil water contents at sowing quickly dry beyond the limits to support chickpea crop establishment [4]. In addition, a large range of aggregate sizes are created in the seedbed of clay-textured soils, from large clods to micro-aggregates. An area representative of this cropping region is in the High Barind Tract of north-west Bangladesh (HBT). Surface soils (0–15 cm) in the HBT have a silty clay texture and bulk densities between 1.4 and 1.6 Mg m^{-3} [5] and are often described as hard-setting clay soils. At 10–12 cm depth, there is usually a clay plough pan layer, a result of continuous paddy rice cultivation [6]. These characteristics of the soil in the HBT lead to a seedbed that is not conducive to chickpea germination or emergence in an environment that quickly dries the surface soil during the relatively short period that is optimal for sowing [6].

As an alternative to broadcast sowing, mechanised row-sowing techniques have been developed for the HBT [7,8]. Mechanised row-sowing decreases the time between rice harvest and sowing of the chickpea crop [9] and is less likely to produce large clods and aggregates within the seedbed. With more timely sowing, the soil water content in the seedbed is likely to remain within the preferred range of soil water potential (ψ, -538 to -33 kPa) favourable to seedling emergence [10]. While the problem of rapidly drying surface soil is likely to be overcome by mechanised row-sowing techniques (e.g., strip planting (SP), zero tillage (ZT), and single-pass shallow tillage (SPST) (see descriptions in Johansen et al. [7]), the soil in the resulting seedbeds has altered soil strength, aggregate size, and bulk density compared to conventional tillage and sowing methods [11]. As the planter is modified from ZT to SP to SPST, the number of rotating blades in front of the furrow opener increases, and the width of disturbed soil increases from the equivalent of the furrow opener width for ZT to an approximately 7 cm wide strip with SP and the entire soil surface with SPST [7,12]. Depending on the soil water content at sowing, this can result in very different aggregate sizes, soil coverage of the seed, and furrow wall conditions among these tillage types compared to the traditional methods.

Under mechanised row-sowing, the physical conditions of the disturbed soil in the seed furrow may limit the emergence of the seed in a number of ways: inadequate seed coverage by the soil if the soil covering the seed is not of an appropriate aggregate size; seed placement is above or below the appropriate depth of moist soil; and smearing on the base and sides of the furrow if the soil is too wet during tillage. One or more of these conditions may lead to accelerated drying of the seedbed soil, poor seed–soil contact, and increased strength of the soil through which the radicle and plumule must penetrate. The development of the shoot may be affected differently by the roots under adverse physical conditions of the soil. Therefore, in a seedbed, the physical conditions of the soil below and above the seed are important. When seed germination and seedling emergence are rapid and roots penetrate the subsurface soils quickly, there is a greater chance of achieving adequate plant stands and, ultimately, good yields. This is especially important in environments like the HBT where cool-season crops like chickpea rely on soil water stored in the profile [13–17].

The development and emergence of the epicotyl and the extensions of early root growth are affected by soil bulk density, soil strength, and aggregate size. As soil strength and bulk density increase, germination and emergence can be delayed, and elongation rates of roots decrease [15,18,19]. Aggregate size can affect the contact of the seed with the soil and, therefore, determine the water uptake of the seed and its germination. In addition, aggregate size can affect the packing of the soil and the size, shape, and number of voids and cracks, which also affects early root growth and seedling emergence [15]. Soil cracks, biopores, and macropores are important for root proliferation through high bulk density soil layers [20,21]. The epicotyl emergence of seedlings can be blocked under surface crusts or under large soil clods [22]. Where the emergence of chickpea seedlings is limited by an impeding layer, such as a soil crust, they have been found to swell to increase their epigeal diameter and exert a greater force to allow them to push through the impeding layer [23]. Where smearing of furrow walls occurs, roots have a tendency to grow parallel to the smeared surface [24], and with less soil disturbance (i.e., no tillage vs. conventional tillage), root development was decreased [25].

Whilst mechanised row-sowing allows timely sowing and mitigates the problem of quickly drying surface soil, soil strength, bulk density, and aggregate size are still soil physical properties that may limit chickpea crop establishment. This study investigated how these soil physical properties limit chickpea emergence and root growth. The objectives of this growth cabinet study were to determine the following:

1. The limitations to chickpea emergence and root growth with increasing bulk density and soil strength; and
2. The extent to which chickpea emergence is limited by different above-seed or below-seed soil physical conditions.

2. Materials and Methods

2.1. Experimental Design

Surface soil (0–10 cm) from Merredin, Western Australia (31° 29′ 52″ S, 118° 13′ 48″ E) was used in these laboratory experiments completed in 2009 and 2010. The soil was characterised as a clay with a bulk density of 1.62 Mg m^{-3} and a particle size distribution of 64% sand, 11% silt, and 25% clay. The Australian soil classification is Calcic Red Dermosol [26]. All soils were air-dried and passed through a 4 mm sieve before use. The Merredin soil was used as it is a soil suitable for chickpea production [27]. The Merredin soil was similar in clay percentage but had a higher proportion of sand and a lower percentage of silt than a representative HBT soil reported in Vance et al. [10] (48% sand, 24% silt, and 28% clay, bulk density 1.4 Mg m^{-3}).

Two growth cabinet experiments were completed to address the objectives. In both experiments, after pre-wetting to a gravimetric soil water content of approximately 50% of field capacity [10], soil was placed in cylindrical PVC pots 15 cm high and 8 cm in diameter. The PVC pots consisted of a separate base (12 cm high) and top (3 cm high) to allow the creation of different soil physical properties above and below the sown seed (Figure S1). One seed was sown per pot at a depth of 3 cm, the depth recommended for field sowing. However, this created a zone of lower strength between compacted layers, which affected seedling emergence, as later discussed. In both experiments, there were ten replicates of each treatment combination. Sowing one seed per pot allowed destructive sampling of the pot once a seedling emerged or to measure the root growth of individual plants at the experiment's end. Seeds of Desi-type chickpea cv. Genesis 836 were used in the two experiments conducted. Seeds were selected for uniformity of size in each experiment. When required, soil water potential was estimated using the water release curve and van Genutchen pedotransfer function [28] derived in Vance et al. [10].

2.2. Details of Experiment 1

Ten replicates of seven treatments of soil bulk density were sown with chickpea seeds in PVC pots with the soil at a constant soil water content. The soil sieved to <4 mm was wet up to the initial soil water contents of 13% (*w*/*w*) and mixed before being left in a sealed container to equilibrate for 48 h. Seven soil bulk density treatments were created at 0.1 Mg m^{-3} intervals from 1.3–1.9 Mg m^{-3} (above which compaction was no longer possible). To construct the soil cores, the soil was placed in 3 cm increments. Seeds were placed before the topmost 3 cm layer was placed. To uniformly compact soil, layers of calculated mass of soil were compacted to a height required for each bulk density. A bench-mounted hand press was used with a circular disc modification to compress the entire surface area of the core (Figure S2).

Penetration resistance was measured with a steel needle with a cone diameter of 2 mm and an angle of 30°. The needle was attached to an advanced force gauge (Dillon AFG 500 N, maximum capacity 500 N, accuracy 0.1%) on a loading frame. The tip of the steel needle was inserted at two locations in the surface of the core where the seed was to be placed, with measurements logged from 0–6 mm depth and the mean force recorded for that depth range.

Each pot was placed in a sun-bag (Sigma-Aldrich, B7026; https://www.sigmaaldrich.com/AU/en/product/sigma/b7026, URL accessed on 29 December 2023). The sealed bag was placed in a growth cabinet at 21 °C and 12 h day/night lighting conditions. Sun-bags are 44 × 20.5 cm, gusseted transparent bags with a 24 mm diameter and a 0.02 µm pore filter on one side. The bags were folded at the top to prevent evaporation; air exchange is then possible through the filter. Gravimetric soil water contents (θ_g) were determined for each treatment at sowing and at harvest. Eight days after sowing, when no shoots had emerged from the soil surface, all pots were removed from the growth cabinet and destructively sampled. The top 3 cm layer of soil had dried significantly. Instead of penetrating through the core, the germinated seedlings pushed up the 3 cm layer and attempted to emerge through the gap between the top and the base soil layers.

2.3. Details of Experiment 2

There were five treatment combinations with ten replicates used to investigate the germination and emergence of chickpea seeds sown to simulate the soil physical conditions under SP or full rotary tillage. The conditions were set to mimic different below-seed bulk densities and aggregate sizes above the seed. Treatment 1 had the same treatment conditions as the 1.3 Mg m^{-3} bulk density, <4 mm aggregates, treatment in Experiment 1. Treatments 2 to 5 simulated two surface soil treatments: <2 mm aggregates, and >4 mm aggregates. Different below-seed soil bulk density was simulated by two treatments: soil compacted to 1.3 or 1.8 Mg m^{-3}. The schedule of five treatment combinations is shown in Table 1.

Table 1. Schedule of treatment combinations used in Experiment 2 to test chickpea germination and emergence with different soil structure conditions. Top core refers to conditions above the seed, while base core refers to physical conditions below the seed.

Core Section	Soil Treatment	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5
Top core	Soil aggregates	<4 mm	<2 mm	>4 mm	<2 mm	>4 mm
	Gravimetric soil water content (%)	14	10	14	10	14
	Bulk density (Mg m^{-3})	1.3	0.98	0.98	0.98	0.98
Base core	Soil aggregates	<4 mm	<4 mm	<4 mm	<4 mm	<4 mm
	Gravimetric soil water content (%)	14	14	14	14	14
	Bulk density (Mg m^{-3})	1.3	1.3	1.3	1.8	1.8

Samples of <4 mm soil aggregates and >4 mm soil aggregates were wet-up to the initial soil water contents of 14% (w/w) and mixed before being left in a sealed container to equilibrate for 48 h. The <2 mm soil aggregate treatment was created by pushing the wet <4 mm aggregate soil through a 2 mm sieve. At the time of potting, the θ_g of the >4 mm and <4 mm aggregate soil was 14%, while it was 10% for the <2 mm aggregate soil. To create the base soil bulk density, the required mass of wet soil was compacted into 3 cm layers. The above-seed <2 and >4 mm aggregate layers were created by pouring 138 g of the wet soil into the 3 cm layer above the sown seed.

Each pot was placed in a sun-bag (see above), and the sealed bag was placed in a growth cabinet at 21 °C, day/night for 12 h. Gravimetric soil water contents were determined for each treatment at sowing and seedling emergence. Fifteen days after sowing, the soil in all remaining pots without emerged seedlings was removed and destructively sampled.

2.4. Plant Measurements

In Experiment 1, seeds were visually inspected to determine if germination had occurred (radicle >2 mm in length), and if so, root and shoot lengths were measured. In Experiment 2, seedlings were monitored for emergence daily. Seedlings were classed as emerged when the shoot tips were first visible on the soil surface. The day of emergence varied across treatments and ranged from day 6 to day 15 (experiment end). The seedling was removed from the pot and destructively sampled when the shoot emerged. In both experiments, roots were handpicked from the soil by carefully breaking the soil clods apart.

Through careful sampling, roots were separated into main and lateral roots as appropriate. Root and shoot length were measured using a scale with 0.5 mm graduations.

2.5. Statistical Analysis

For Experiment 1, Analysis of Variance (ANOVA) was used to test the main effect of bulk density treatment on variables of root length and penetration resistance. The least significant difference (LSD) at the 5% level was used to distinguish differences between treatment means. In Experiment 2, the effects of soil water content, bulk density, and aggregate size on germination, emergence, and chickpea growth characteristics were analysed by Residual Maximum Likelihood (REML) because of unequal replication of treatment combinations. The fixed effect model included replicate as the blocking term, with the main effects of bulk density and aggregate size and the interaction of these included in the model. Where REML was used, the estimated means from the model were reported. All analyses were carried out with GenStat V11.1 (VSN International Ltd., London, United Kingdom).

3. Results

Experiment 1 investigated chickpea emergence and shoot characteristics with increasing bulk density. Pots were destructively sampled eight days after sowing. At this time, there was no difference among treatments in water contents, with the mean θg below the seed at 13.3 ± 0.07% and that above the seed at 8.2 ± 0.15%. Shoot length was limited due to the inability of shoots to penetrate through the compacted upper layer of the pots. No chickpea shoots emerged in any bulk density treatment. Shoots attempted to grow in the gap between the soil of the upper and lower layers. The shoot lengths were between 0.45–1.5 cm, with no significant difference among treatments.

The mean root length was greatest in the soils at 1.3 Mg m^{-3} bulk density and decreased by 84% with increasing bulk density to 1.9 Mg m^{-3} (Figure 1). Root length was significantly reduced by increased bulk density ($p < 0.001$), but generally root length was not significantly different between treatments differing in bulk densities by increments of only 0.1 Mg m^{-3} (Figure 1). This was the case for the length of both the main roots ($p < 0.001$) and the lateral roots ($p = 0.01$) (Figure 2a,b).

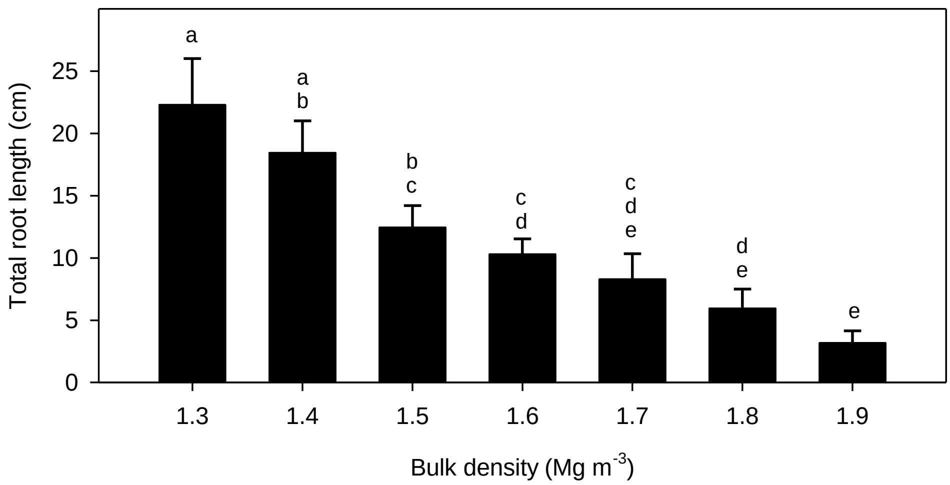

Figure 1. The total root length (cm) of chickpea seeds sown in soils compacted to bulk densities between 1.3 and 1.9 Mg m^{-3} in Experiment 1. Mean root lengths with identical letters (a to e) are not significantly different. Vertical bars indicate 1 standard error of the mean.

Soil penetration resistance in the below-seed layer increased with bulk density from 0.58 to 1.34 MPa (range of 1.3 and 1.9 Mg m^{-3} bulk density treatments, respectively) ($p < 0.001$) (Figure 3). Treatments with low bulk density (1.3–1.4 Mg m^{-3}) had significantly lower resistance than those with high bulk density (1.8–1.9 Mg m^{-3}). With increasing soil penetration resistance below the seed created by the bulk density treatments, root length decreased (Figure 4).

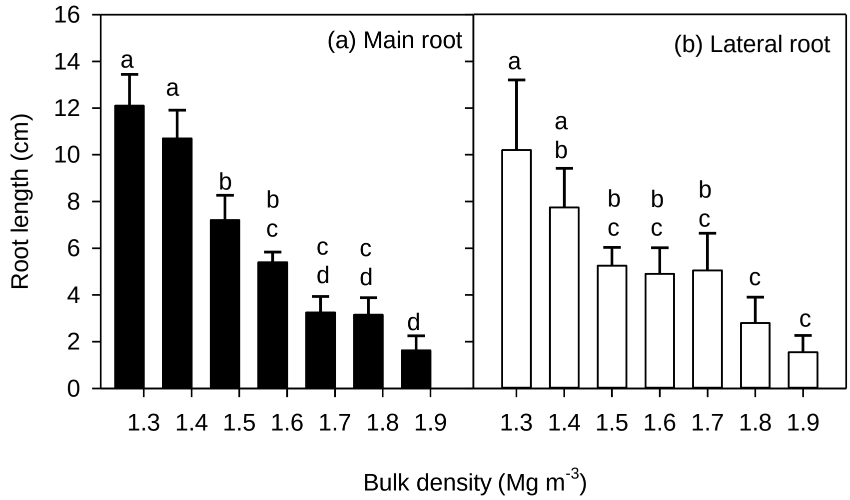

Figure 2. The main root (**a**) and lateral root (**b**) length (cm) of chickpea seeds sown in soils compacted to bulk densities between 1.3 and 1.9 Mg m^{-3} in Experiment 1. Mean root lengths with identical letters (a to c) are not significantly different. Vertical bars indicate 1 standard error of the mean.

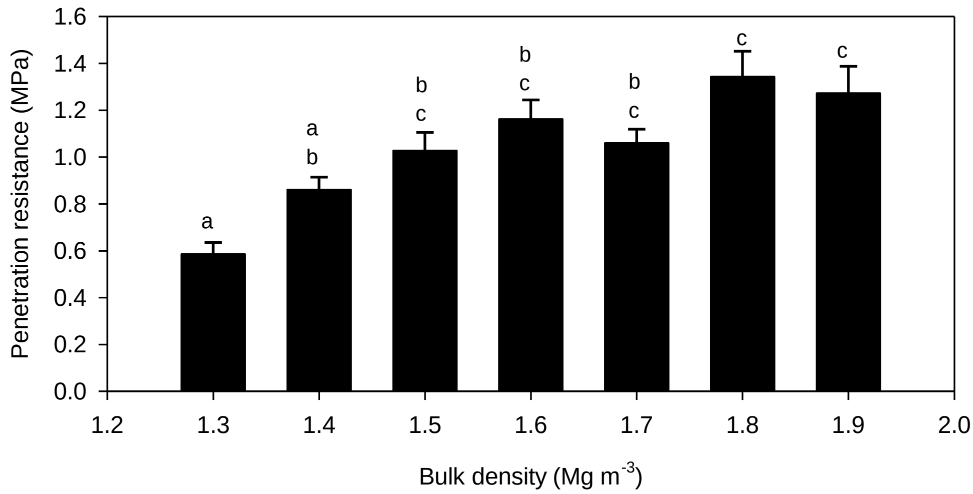

Figure 3. The mean soil penetration resistance (MPa) of the below-seed layer at sowing of the chickpea seeds into soils compacted to bulk densities between 1.3 and 1.9 Mg m^{-3} in Experiment 1. Mean penetration resistance bars with identical letters (a to c) are not significantly different. Vertical bars indicate 1 standard error of the mean.

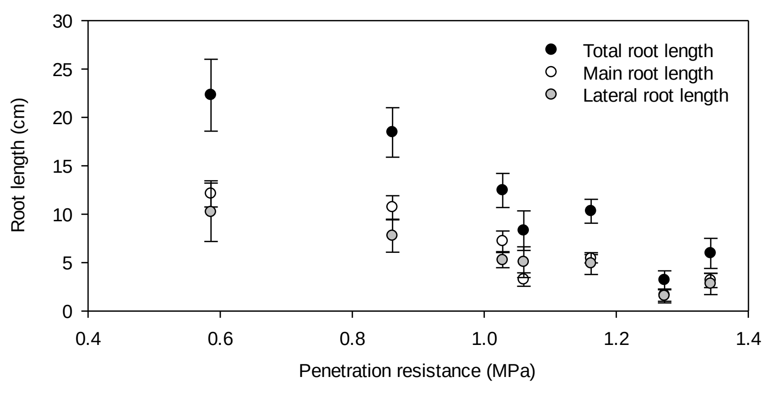

Figure 4. The relationship between mean soil penetration resistance (MPa) of the below-seed layer at sowing of the chickpea seeds and mean root length in Experiment 1. The soil was compacted to bulk densities between 1.3 and 1.9 Mg m^{-3}. Vertical bars indicate ± 1 standard error of the mean.

Cultivated seedbeds have differentially compacted soil with depth in the seedbed. Therefore, Experiment 2 investigated the effect of different aggregate sizes and uncompacted soil above the seed in combination with two levels of below-seed bulk density. The soil water content was kept constant throughout the core.

At sowing, the θ_g of the below-seed and the above-seed <4 mm and >4 mm aggregate sizes were all 14%, while for the above-seed <2 mm aggregate size, θ_g was 10% (Table 1). The loss of 4% soil water at sowing may have been due to the preparation of the <2 mm aggregate size soil, which allowed evaporation from the soil just prior to sowing. The sampling for θ_g occurred at sowing, when it was too late to compensate for water loss due to evaporation.

Regardless of treatment, at harvest, the mean θ_g of the below-seed soil was between 11.8 and 12.5%, and the above-seed soil was 5.8–8.3% (Figure 5). There were no significant differences in below-seed soil water contents among treatments. However, the mean soil water contents of the above-seed soil were lower in the <2 mm aggregates and highest in the >4 mm aggregates.

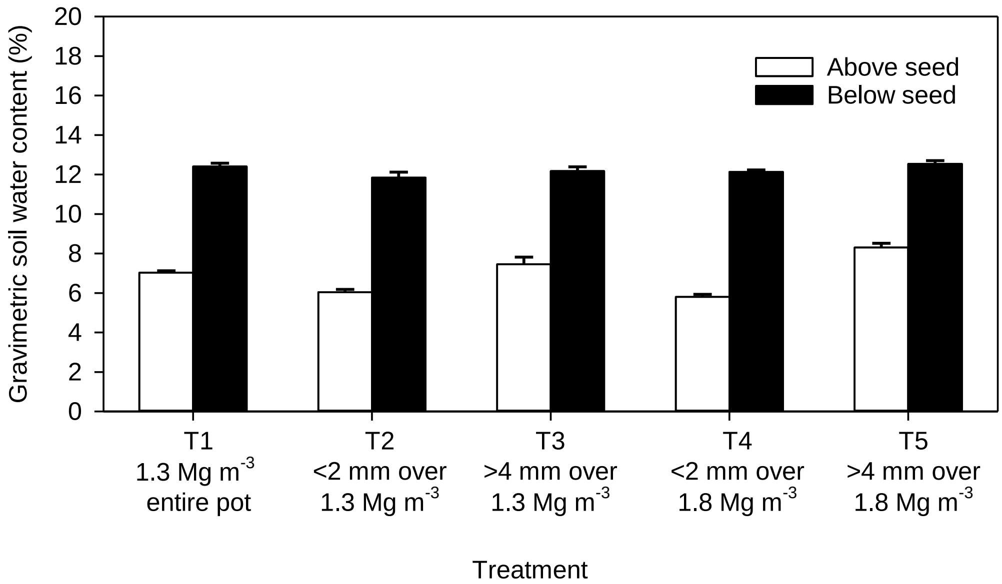

Figure 5. Gravimetric soil water content (θ_g) above and below the seed at harvest for Experiment 2. Values are means of 10 samples, regardless of harvest date. Vertical bars indicate 1 standard error of the mean where visible.

The ten seeds in each treatment were classified as either emerged or not-emerged. The not-emerged seeds were further classified as having root and shoot development, root development only, or not-germinated. Table 2 summarises the germination and emergence characteristics of the seeds in each treatment. The first seedling emerged in T3 (>4 mm, 1.3 Mg m^{-3}) on day 7. However, the fastest rate of emergence was in T5 (>4 mm, 1.8 Mg m^{-3}), followed by T3 (Figure 6). These treatments both had >4 mm aggregate size in the above-seed soil but different below-seed soil bulk densities. No treatment had 100% emergence: the best were T3 and T5 that had 80% emergence, whilst T2 (<2 mm, 1.3 Mg m^{-3}) and T4 (<2 mm, 1.8 Mg m^{-3}) had 60 and 40% emergence, respectively, and T1 (1.3 Mg m^{-3} entire pot) had no emergence (Table 2). In T2, T3, and T5, there was a peak in emergence during 8–10 days, while T4 had a constant emergence of 1 new seed per day (Figure 6).

Table 2. The growth of chickpea seeds at harvest in Experiment 2. Seeds were classified as either emerged (%), not-emerged but with root and shoot development (%), not-emerged with root development only (%), or not-germinated (%). Each treatment has a total of 10 seeds.

Treatment	Treatment Description (Above-Seed Aggregates Size, Below-Seed Bulk Density)	Emerged (%)	Not-Emerged Root and Shoot Development (%)	Not-Emerged Root Development Only (%)	Not-Germinated (%)
T1	T1, 1.3 Mg m^{-3} entire pot	0	70	30	0
T2	T2, <2 mm over 1.3 Mg m^{-3}	60	30	0	10
T3	T3, >4 mm over 1.3 Mg m^{-3}	80	10	0	10
T4	T4, <2 mm over 1.8 Mg m^{-3}	40	30	30	0
T5	T5, >4 mm over 1.8 Mg m^{-3}	80	20	0	0

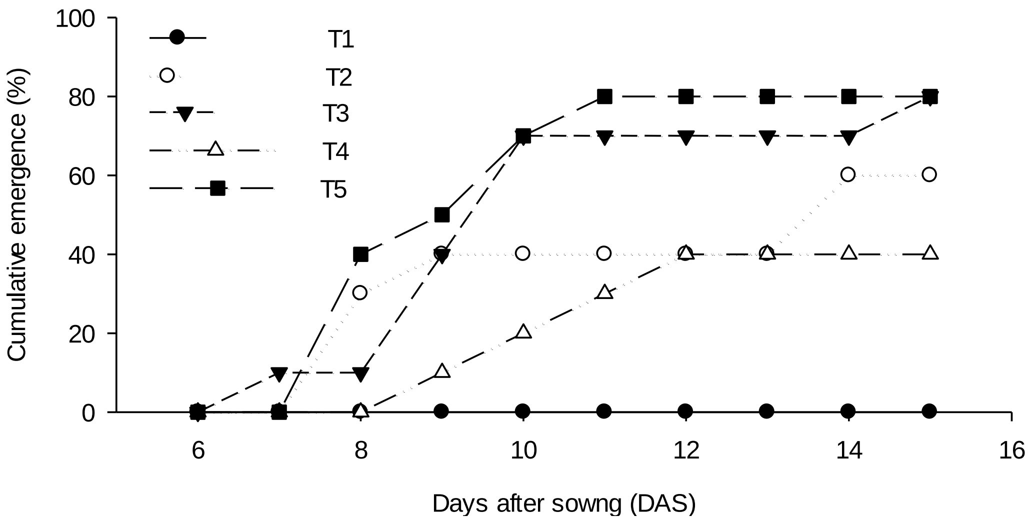

Figure 6. Cumulative emergence of chickpea seedlings sown in Merredin soil in Experiment 2. Treatments were combinations for layers above or below the seed. Treatments—T1, 1.3 Mg m^{-3} entire pot; T2, <2 mm over 1.3 Mg m^{-3}; T3, >4 mm over 1.3 Mg m^{-3}; T4, <2 mm over 1.8 Mg m^{-3}; T5, >4 mm over 1.8 Mg m^{-3}.

The fastest rate of emergence was in the soils with >4 mm aggregates above the seed, regardless of bulk densities below the seed. The increased aggregate size improved germination and emergence. This may have been due to the slight increase in θ_g of these treatments compared to the <2 mm treatment. It could also be due to how the smaller-diameter aggregates packed together, which inhibited the emergence of the shoot.

When only emerged seeds were considered, the main root length was less in the soils compacted to 1.8 Mg m^{-3} bulk density (3.1 cm in T4 and T5) compared with the 1.3 Mg m^{-3} bulk density (5.9 cm in T2 and T3) (p = 0.001) (Figure 7a). In contrast, the lateral roots of the seed in the 1.8 Mg m^{-3} bulk density soils were greater in length than in the 1.3 Mg m^{-3} bulk density soils, 7.8 cm and 3.6 cm, respectively ($p < 0.001$). This confirmed the visual observation that the main roots in the 1.8 Mg m^{-3} bulk density soils were short, thick, and curled, and the lateral roots grew across the interface of the base and top core along the path of least resistance. Total root length was not different among treatments. The aggregate size of the surface soil did not affect the root growth of the chickpea seedlings.

All the pots where no seedlings emerged were harvested on day 15. In soils compacted to 1.3 Mg m^{-3} throughout the pot (T1), all the seeds germinated, and 70% had shoot growth (Table 2). Although the pots in T1 had no shoot emergence, they did have a mean total root length of 24.4 cm, which was greater than the mean total root length of the other not-emerged seeds in other treatments (Figure 7b). Where the soil was compacted above and below the seed to 1.3 Mg m^{-3} (T1), shoot growth was restricted, but seedlings all had some shoot growth as the seedling attempted to find a pathway to emerge from the soil.

Of the other treatments where seeds did not emerge, with the exception of T5, the root growth was less than that of the emerged seeds of the corresponding treatment. This suggests that root growth was limited in these seeds, which may have been limiting emergence.

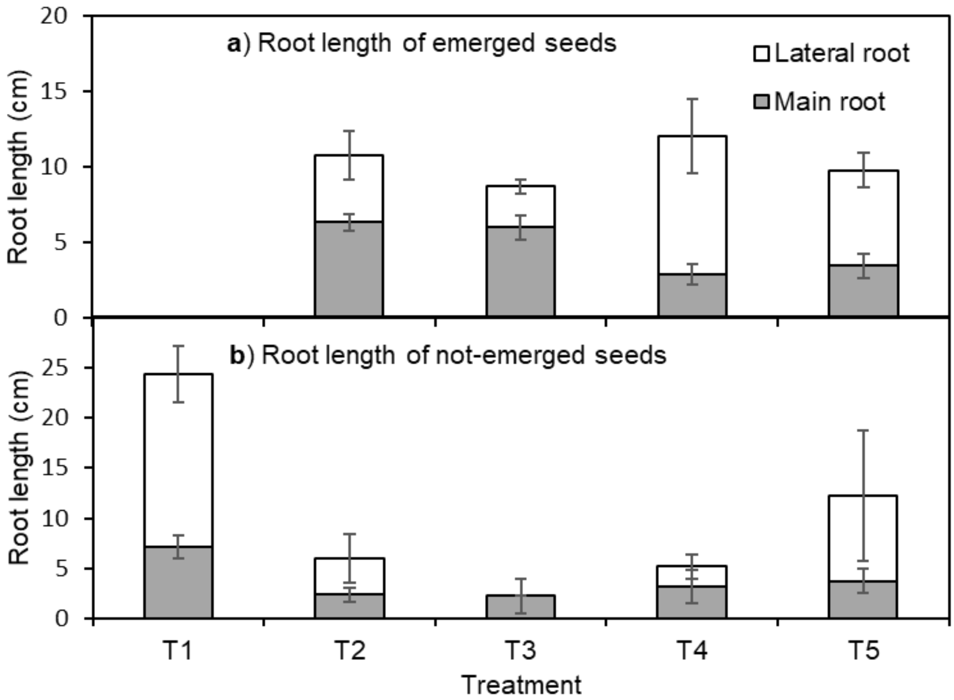

Figure 7. Main root and lateral root for (**a**) the seeds that did emerge and (**b**) the seeds that did not emerge in Experiment 2. Vertical bars indicate 1 standard error of the mean. The numbers of emerged seeds in each treatment are given in Table 2. Treatments—T1, 1.3 Mg m^{-3} entire pot; T2, <2 mm over 1.3 Mg m^{-3}; T3, >4 mm over 1.3 Mg m^{-3}; T4, <2 mm over 1.8 Mg m^{-3}; T5, >4 mm over 1.8 Mg m^{-3}.

4. Discussion

4.1. Seedling Emergence

In this study, the prime interest was in the early growth of the chickpea seedlings and, most importantly, the soil physical properties that determine whether roots could penetrate the drying surface soil and distribute into the wet soil below. In previous pot experiments where the seed was sown into uncompacted soil (<4 mm sieved soil) and covered loosely (essentially a dibbling technique), there was delayed emergence at low water contents of 12% θ_g (ψ of −220 kPa) [10]. By contrast, in the experiments of this study, where the seed was placed under a compacted layer of soil (packed to bulk densities of 1.3 Mg m^{-3} and greater above the seed, at 13% θ_g; ψ of −182 kPa), there was no emergence. Seedling emergence can be limited when blocked under clods or crusts [22], and in this study, shoots tended to grow into the gap created by the two soil layers, regardless of the soil bulk density or strength above it. However, the shoots were unable to penetrate through the surface of the core, indicating that in a seedbed with uniform compaction above the seed, emergence may be limited, even though shoots have the ability to develop in gaps and to push apart what essentially in this experiment acted as a large clod face (8 cm diameter). This limits the extrapolation of the seedling emergence results of Experiment 1 to field conditions. Experiment 2 better represents field conditions similar to those found in seedbeds prepared with mechanised sowing techniques such as SP, ZT, or SPST. In a seedbed prepared via SP, ZT, or SPST, seedlings are unlikely to be confined below a large clod of high strength. In the broadcast seeding system, following two or more passes of rotary tillage, there will likely be a distribution of aggregates from small to large diameters, plus clods, in the seedbed layer. Hence, the seedling emergence of chickpea is likely to be limited but not prevented by the presence of larger clods with broadcast seeding. In this present study, there is evidence that chickpea seedlings have the ability to emerge around large clods above a seed by making use of gaps between the clods and aggregates. Chickpea seedlings respond to impeding conditions by swelling and increasing their epigeal diameter, allowing them to exert more force to push through surface crusts [23]. The delay in seedling emergence in compacted soil, where the volume of voids in the soils was reduced, can be due to the increase in the length of the pathway the seedling shoot must take to reach the soil surface [15].

Seedling growth after emergence has also been reported to be affected by increased soil strength due to indirect responses such as inhibition of root growth in wheat (*Triticum aestivum* L.) [29]. In a study by Choudhary et al. [30], chickpea plant height and biomass were decreased by 40 and 72%, respectively, with an increase in soil bulk density from 1.2–1.6 Mg m^{-3} (measured 17 days after sowing). This decrease was attributed to restricted root growth in compacted soil due to decreased water and nutrient supply. However, other research with pigeonpea (*Cajanus cajan* L.) suggested that in soils where there was unlimited root growth in some layers and access to water and nutrients was not limiting, shoot growth may not be limited by other layers with zones of high soil strength [14].

Chickpea seeds emerged (40 to 80% success) from soil where the seed was covered by loosely packed aggregated soil, regardless of the soil compaction below the seed. In this present study, the soil that had the greater aggregate size of >4 mm had the fastest rate of emergence, regardless of below-seed soil bulk density. By contrast, in previous studies in cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L), and wheat, finer aggregates (<4 mm) were generally associated with an improved rate and final emergence due to better seed–soil contact and water uptake to the germinating seed [15,31]. The contrasting effects of aggregate size on emergence to those of previous research [15,31] were attributed to the soil water content of the above-seed soil rather than the soil physical factors of aggregate size or soil strength. Aggregate size distribution has been found to have less influence on seedling emergence than soil water potential [32]. In the present study, the water content of the <2 mm aggregate layer was 4% lower than the >4 mm aggregate layer, which may also have delayed germination. The θ_g was 10% above the seed in the <2 mm aggregate size layer, less than the minimum required for successful emergence reported at θ_g of 12% by Vance et al. [10]. In this case, the movement of water from the soil to the seed would limit water uptake [33]. However, the θ_g below-seed was 14%, which should compensate for the lack of water contributed by the above-seed soil to the seed, and still allow germination and emergence to occur, albeit with a delay.

The low bulk density (1 Mg m^{-3}) and soil strength (below 0.2 MPa) above the seed in the present study, for both aggregate sizes, were also discounted as limiting factors to shoot emergence by chickpea. Loose soil with a bulk density of 1 Mg m^{-3} and soil strength 0–0.031 MPa has a negligible effect on plant root growth [34], and given the ability of the shoots to move the compacted soil (3 cm layer) above the seed in Experiment 1, the elongation of the emerging shoot was unlikely to be limited by these small aggregates. Penetration resistance of loosely packed, low bulk density soil will be low regardless of the aggregate size; only at higher bulk densities will penetration resistance register differences [15]. In addition, Kirkegaard et al. [14] found no direct effect of soil strength on shoot height when the germinated seeds of wheat were sown above a compacted layer and soil was pressed over the seeds. In Vance et al. [10], when the seed was dibbled into loose soil, elongation of chickpea shoots was uninhibited due to no compaction of the soil above the seed.

4.2. Root Elongation

The roots of the seedlings were significantly impeded as bulk density and soil strength increased. The elongation rate of radicles in many species has been shown to follow an inverse response to increasing soil strength, with 2–3.7 MPa being the critical threshold of soil strength at which radicle elongation for various species stopped [14,35]. Kirkegaard et al. [14] also found that the elongation of the radicles of pigeonpea was more sensitive to high soil strengths than the growth of subsequent seedling roots. The roots respond to increasing soil strength by increasing the root diameter behind the root tip and decreasing root elongation [35]. In the present study, the root length of chickpea was depressed at soil strengths of 1.3 MPa, but soil strength did not totally inhibit root growth, and main root and lateral roots were equally affected. A main root length of 12 cm or more indicated unlimited root growth under soil strengths of 1 MPa, as this was where the roots reached the base of the pot. At soil strengths greater than 1 MPa, root lengths were depressed by 50% or more. As the strength of a compacted layer increases, the proportion of roots that penetrate it will decrease [21]. Plant roots under impedance exert a growth pressure that enables them to elongate through voids in the soil that are smaller than the root diameter by displacing soil and overcoming friction [36]. The maximum impedance where root elongation is no longer possible has been reported to vary with species and the measurement method [37]. Lateral roots are finer than main roots and, as such, should be able to penetrate smaller pores [37]. However, compaction apparently increased the proportion of small pores and, hence, would also have decreased both lateral and main root elongation.

Root elongation could also be limited by oxygen availability. In the soil compressed to 1.8 and 1.9 Mg m^{-3}, more water was contained within the soil matrix [14,34]. At these high bulk densities of 1.8 and 1.9 Mg m^{-3}, the air-filled porosity was less than 7.5%, which can limit oxygen supply and limit root growth [38]. High bulk density limited the development of chickpea seedling roots due to limiting soil strength and aeration, even at soil water contents that were dryer than optimum in the previous germination and emergence experiments.

In Experiment 1, in soil under uniform compaction (1.3–1.9 Mg m^{-3}) above and below the seed, shoot emergence did not occur, while main root and lateral root growth both decreased to the same degree with increased bulk density. Similarly, Choudhary et al. [30] found a 77% decrease in main root length and an increase in root diameter in chickpea seedlings with an increase in soil bulk density of 1.2–1.6 Mg m^{-3}. They estimated the critical bulk density at which root growth stopped as 1.9 Mg m^{-3}. In Experiment 2, where the above-seed soil was loosely packed, total root growth was not different in the emerged seedlings when the soil below the seed was compacted to 1.3 or 1.8 Mg m^{-3}. However, at the two bulk densities, the seedlings exhibited different root growth characteristics. At the low bulk density (1.3 Mg m^{-3}), the main root of seedlings grew unimpeded to the base of the pot and produced minimal lateral roots. In the highly compacted below-seed soil (1.8 Mg m^{-3}), the seedling was unable to send the main root directly through the soil and, in response, produced lateral roots, which grew in the gap between the surface and base layers of the pots, the path of least resistance. When main roots are slowed in growth due to a compacted layer, the proliferation of lateral roots in the unconfined layer above can occur [14]. This type of response is common among plant species and can also occur due to low water content, high soil strength, and larger aggregates dominating [21]. For chickpea that encountered soil compaction in this experiment, the total root length was 9.7 cm (T4) to 12 cm (T5), with 76 and 64% of that root length, respectively, being contributed by the lateral roots. With a uniform bulk density of 1.8 Mg m^{-3} throughout the core, the total root length was 5.9 cm, 47% of which was contributed by lateral roots. In fact, in all the uniformly compacted pots after eight days, lateral root length made up 47 $\pm$ 2% of the total root length (Figure 2). At high bulk densities, soil cracks, biopores, and macropores are important for root proliferation through soil [20]. It has been found that roots were able to elongate into cracks of equal or greater width than the root tip diameter [21]. In the pots with loose surface soil, the lateral roots that developed and accessed the interface between the hard layer and the loose surface would have had very little resistance to elongation and would not have needed to generate much force to grow between these two layers.

4.3. Implications for Field Conditions

The present results can be related to chickpea emergence in a field study carried out in the HBT where seeds were sown in one pass with mechanised row-sowing [12]. Field measurements of soil strength were from 0.38–1.99 MPa directly before sowing, 0.45–0.72 MPa in the seed row after sowing, and 1.5 MPa when monitored after final emergence [12]. With the later sowing dates (ranging from 22 November to 22 December), the soil strength increased due to lower soil water contents. In the present pot trial, soil strength began to impede root growth at >1 MPa. The values in the field trials indicate that soil strength was not limiting in the seedbed directly after sowing. After emergence, with continued soil drying in the seedbed, soil strength could have been limiting root growth. However, following emergence, the roots of the chickpea plant should have grown out of the cultivated layer and into the deeper, uncultivated soil. Soil strength would then depend on the soil structure and soil water content of the uncultivated soil. The bulk density of the 10 to 15 cm layer in the field was 1.4 Mg m^{-3}, and the soil water content was between 13 and 17%. Results from the pot trials indicate that at these values, the elongation of the main root downwards and lateral root growth should not be limited in field conditions.

In seedbeds where hard layers exist under the surface soil layer, the effect of an increase in bulk density may result in root growth being confined to the surface soil. Such hard layers may develop with the drying of the surface soil when there are large aggregates in the seedbed or if there are soil textural changes in the profile [21]. In the HBT, hard layers may develop at a depth of 10–15 cm due to the cultivation techniques and puddling of the soil for rice production in the kharif season [6]. The early root growth of the confined root system may then be concentrated in the fast-drying, shallow surface layer, which may compromise early plant growth. The role of mechanised tillage in alleviating or exacerbating the strength of a hard pan is therefore critical in determining the success of crop establishment, but this needs further investigation [39,40]. In addition, when the seedbed is created by mechanised tillage equipment, the trafficking by the farm machinery can create compacted surface soils, which limits seedling emergence [41]. However, there are benefits to some compaction of the soil above the seedbed to improve seed/soil contact and retain soil water for crop establishment and growth [42].

Further field studies that investigate seedbed properties after sowing are needed to determine which tillage equipment creates a non-limiting environment for crop establishment. The limiting thresholds of soil water, soil aeration, and soil strength determined for chickpea germination and emergence can be tested on field sites to establish whether they predict the successful establishment of chickpea. If so, further studies would be useful to define limiting thresholds for other crop species and soil texture classes.

5. Conclusions

This work suggests that the above-seed and below-seed soil physical properties will impact independently on the early growth of the chickpea seedling and that at adequate levels of soil water content, the soil bulk density and soil strength can limit chickpea emergence. At a soil strength of <1 MPa, root growth was unimpeded, whilst at a soil strength of 1.3 MPa, root growth was impeded. Within the root system of the chickpea seedlings, impeded downward growth of the main root due to high bulk density soil was compensated for by increased length of lateral roots. This was more pronounced when there were pockets of high-porosity, low-strength soil they could penetrate. In the present study, low strength occurred at the interface between the core layers where the seed was placed, and subsequent shoot development occurred along this interface. The shoot forced the core layers apart, which allowed preferential growth of the lateral roots. The soil above the seed needs to be loosely compacted (<1.3 Mg m^{-3} bulk density), but the size of the soil aggregates that provide the best germination and emergence could not be determined conclusively. Large clods and high bulk density layers above the seed will limit seedling emergence, whilst high bulk density below the seed will limit seedling root elongation. When compared to field studies, the response of the seedlings to high bulk density and soil strength in this glasshouse study indicates that root elongation of seedlings may be limited in the medium-to-heavy-textured soils of the Indo-Gangetic Plain in the rapidly drying surface soil of the rabi season.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/seeds3010003/s1. Figure S1: Pot construction to ensure consistent soil physical properties below and above the chickpea seed in Experiments 1 and 2; Figure S2: Bench mounted hand press (a), PVC pipe (b) and circular disc (c) used to construct the cores in Experiments 1 and 2.

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