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Enhancing Canola Seed Quality Under *Rhizoctonia solani* Stress Through Seed Pelleting

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ABSTRACT

Canola (*Brassica napus* L.) seeds are small and exhibit significant variability in size, resulting in a decreased emergence percentage (EP) and reduced uniformity in the field. Additionally, canola seedlings are susceptible to *Rhizoctonia solani* in the early growth stages. This research aimed to investigate the effects of seed pelleting with different fillers, binders and biomaterials on canola's emergence quality, early growth and seedling health. The first experiment was conducted in the seed laboratory and greenhouses. The treatments included four types of fillers: calcium sulphate + zeolite (CS + Z), calcium sulphate + talc (CS + T), calcium sulphate + calcium carbonate (CS + CC) and calcium carbonate + bentonite (CC + B). Additionally, three types of binder materials were evaluated: gum arabic, selenium dioxide and carboxymethylcellulose. The results showed that the composition of carboxymethylcellulose as a binder, combined with a filler mixture of calcium sulphate and calcium carbonate, significantly increased the emergence rate and early growth compared to non-pelleted seeds. Furthermore, this seed pelleting treatment did not adversely affect seed emergence. The highest emergence rate (0.185), leaf area (3.94 cm²), shoot growth rate (0.019 cm day⁻¹), leaf chlorophyll content (41.03), plant length vigour index (3543), root value (1.35) and plant weight vigour index (26.66) were observed in seeds pelleted with a composition of CS + CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹), and carboxymethylcellulose (30 g carboxymethylcellulose per 10 g seed⁻¹). Because the seeds pelleted with this combination had the highest sphericity, pelleting efficiency and the lowest fragmentation number and dissolution time. The second experiment evaluated the effects of four levels (0, 500, 1000, 1500 and 2000 mg g⁻¹) of extracts from *Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus*. The results showed that *T. vulgaris* extract at a concentration of 2000 ppm significantly controlled the growth of *R. solani*. The third experiment was conducted in the seed laboratory and greenhouses. The treatments included pelleted seeds with the same superior treatment as in the first experiment (CS + CC (200 g/10 g⁻¹ + 50 g/10 g⁻¹) + CMC₂ (30 g/10 g⁻¹)), to which four medicinal plant extracts (*T. vulgaris*, *L. officinalis*, *C. verum* and *S. rosmarinus*) and five concentrations (0, 500, 1000, 1500 and 2000 ppm) were added. The results showed that the highest percentages of emergence (67%), emergence rate (0.085 seeds per day), leaf number (9.6), shoot dry weight (0.42 g), root dry weight (0.35 g) and seedling vigour index (57.49) were observed in seeds pelleted with 2000 ppm *T. vulgaris* extract. In conclusion, the use of a combination of calcium sulphate, calcium carbonate and carboxymethylcellulose for seed pelleting, alongside *T. vulgaris* extract as an environmentally friendly antifungal agent, has been shown to enhance the quality of canola seeds and improve the disease resistance of canola seedlings in soils infested with *R. solani*.

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1 | Introduction

Canola (*Brassica napus* L.) is the second most important oilseed crop in the world after soybeans (Foreign Agricultural Service/USDA 2018; Friedt et al. 2018). It is widely used as a source of oil and protein in food and industrial products (Raboonatahiry et al. 2021). In Iran, the area dedicated to canola cultivation has increased significantly in recent years. While the harvested area was around 3300 ha in 1998, by 2017 this had grown to approximately 102,568 ha, producing 181,148 t (Fao, F.A.O.S.T.A.T 2018). This dramatic increase reflects the growing importance of canola in Iran's agricultural landscape. Canola seeds are smaller than most grains and oilseeds. Natural variability in seed size is one of the physical characteristics of canola seed traits (Faraji 2014). The 1000-seed weight for canola typically ranges from 1.9 to 4.6 g, categorising it as 'small' to 'large' (Elliott et al. 2007; Razavi 2006). Uniform canola seed size is crucial, as variations can lead to problems during planting and seedling establishment. Seedling establishment is a critical factor in the profitable and sustainable production of small-seeded crops such as canola.

Pelleting small canola seeds can improve their uniformity, leading to better seedling establishment and increased yield (Jyoti and Bhandari 2016). Seed pelleting is a pre-sowing technology in which small, irregular seeds are coated with different materials such as fillers, binders, and, in some cases, bioactive or chemical agents (such as nutrients, fungicides or micronutrients) to achieve a uniform, spherical and standardised-sized structure (Javed and Afzal 2018). This process is performed to improve the efficiency of mechanised planting, uniform seedling establishment, increase water and oxygen uptake capacity and protect seedlings against environmental stresses and pathogens (Javed et al. 2022; Zaim et al. 2023). The choice of the type and ratio of materials used in pelleting depends on the physical characteristics of the seed and the ecological conditions of the planting site (Abdukerim et al. 2023). Seed treatment and other additives must be compatible with the filler and binder materials used in the pelleting process. Appropriate dosages of these components need to be standardised to avoid excess. For seed pelleting, fillers such as peat, talc, bentonite and diatomite are selected due to their physical properties and neutrality. These materials are added to the seed along with the binder and cause the formation of larger, round seeds that facilitate mechanised planting and uniform seed distribution in the field (Abdukerim et al. 2023). The type of binder used plays an important role in the quality and performance of the pellet (Aransiola et al. 2019; Olugbade et al. 2019). Carrier materials can also incorporate additives such as micronutrients and plant protectants (Smith and Miller 1987). Calcium sulphate (CS) is a common seed pelleting agent (Jeepheet et al. 2022) that improves the physical properties of seeds such as hardness, friability and water resistance, and consequently increases germination efficiency. In recent studies, a combination of CS and methyl hydroxyl ethyl cellulose (MHEC) has been used to pelletize marigold seeds (Kangsopa et al. 2023; Chaiyasarn and Siri 2019). Another carrier material commonly used for seed pelleting is calcium carbonate (CC). It offers several benefits, including providing a protective seed coating, promoting seed-to-soil contact and enhancing the conditions for successful seed germination and plant growth. Other researchers used a monolayer of CC (Im et al. 2020), CC and CS, its bilayer with bentonite(B) and zeolite(Z) for pelleting small-sized lettuce seeds

(Jyoti and Bhandari 2016). However, the type of suitable binder depends on the specific seed type (Kangsopa et al. 2023). One commonly used gum arabic (GA), a natural adhesive material. It is often incorporated into seed coating solutions used in pelleting processes, alongside other materials like sodium alginate (SA) and CMC (Wu et al. 2024). The use of gum arabic (GA) in combination with other carrier materials can improve the physical properties and performance of seed pellets. Methyl cellulose (MC) has also been used as a binder in combination with fillers such as peat moss and lime (Jyoti and Bhandari 2016). Also, the use of selenium dioxide (SD) and calcium peroxide (CP) in seed pelleting has been reported to increase germination, improve seedling growth and facilitate crop establishment in different environmental conditions (Kangsopa et al. 2023; Mei et al. 2017).

Seed treatment is a suitable strategy to reduce the damage caused by pathogens to the seedling and to ensure a healthier and stronger establishment of the plant (Javed et al. 2022). It is important to note that *Rhizoctonia solani* is one of the primary pathogens responsible for root rot and damping-off diseases in canola, along with *Fusarium* and *Pythium* species (Kataria and Verma 1992). Various methods have been explored for controlling *R. solani*. Most of these methods recommend the use of pesticides, which cause environmental pollution; however, it is better to use environmentally friendly inhibitory compounds. One of the most effective approaches has been the use of plant extracts to control this fungal pathogen (Amini et al. 2012). Some plant extracts can enhance the natural defences of plants and protect against diseases. For example, thyme (*Thymus vulgaris*) extract has been identified as a biocontrol agent against *R. solani* (Chauhan et al. 2017). Also, ethanolic extract (Behiry et al. 2022) of *Plantago lagopus*, clove extract (Kangsopa et al. 2023), essential oils of thyme and lavender (*Lavandula angustifolia*) (Aktaruzzaman et al. 2020) and cinnamon (*Cinnamomum verum*) extract have shown antifungal properties and inhibit the growth of this pathogen and are suggested as effective biological control strategies (Khaleedi et al. 2015). Other research suggests that plant extracts such as rosemary (*Salvia rosmarinus*), cinnamon, thyme and lavender have strong antifungal activity against *R. solani* and can be effective in controlling this pathogen (Aghazadeh Naeini et al. 2022; Aamer et al. 2023). Natural variability in canola seed size can lead to various planting challenges, including missed seeding, double or triple seeding and uneven emergence rates. These inconsistencies can negatively impact crop performance and yield potential. On the other hand, the seeds of rapeseed seedlings are sensitive to *Rhizoctonia* root. This disease poses a major threat to canola production. To address this issue, seed pelleting to apply *Rhizoctonia* root control substances on canola seeds can be an essential practice for canola cultivation (Ramzan et al. 2016). Some of the plant-based compounds may have potential as natural fungicides. Plant-based compounds have significant potential as natural fungicides due to their eco-friendliness, reduced toxicity and ability to combat fungal pathogens effectively (Chauhan et al. 2017). However, the development and evaluation of specialised seed coating formulations are crucial for effective utilisation across different plant species and agronomic purposes. This is because the type of binder and coating material suitable for a particular seed may vary. When choosing fillers, binders and natural fungicides for canola seed pelleting, the following important criteria should be considered: Easy availability and accessibility in

the local context (e.g., Iran), particle size of less than or equal to 250 µm, high capacity to absorb and store water, and non-toxicity to canola seeds. The objective of this experiment was to identify the appropriate type and concentration of binder, filler and natural fungicide material for pelleting canola seeds to enhance emergence, seedling growth and overall seedling health after the seed pelleting.

2 | Materials and Methods

2.1 | Experiment 1: Evaluating Binder and Filler Treatments on the Emergence and Early Growth of Canola Seeds

This experiment was conducted to identify the optimal combination of binder, filler and plant-based compound treatments for use as seed coatings on canola. This study was conducted in 2023 in a greenhouse and laboratory. The primary hypothesis was that the stability of the seed coating materials would not cause any damage to the seeds during the early stages of growth in the field. For more details, see the [Supporting Information](#).

2.1.1 | Seed Materials

The commercial Dalgan variety of canola seeds was obtained from the Oil Seed Crops Research division of the Seed and Plant Improvement Institute, Karaj, Iran. The seeds were harvested from the field in September 2022. The seed moisture content was reported to be about 12%, with a germination capacity of 98%. However, to ensure greater certainty before the experiment, the germination capacity of the seeds was evaluated by conducting a standard germination test using a completely randomised design with four replications (Allen and Alvarez 2020). The seeds were stored in plastic bags at 5°C until the start of each experiment.

2.1.2 | Method of Seed Pelleting and Coating Materials

At first, the 10g of homogenised seeds were disinfected with 8% calcium hypochlorite for 5 min. The motorised seed pelletizer consists of a direct current (DC) power gear motor and a hemispherical pelletising pan; the speed of the coating pelletising pan was fixed at 40 rpm (revolutions per minute). For seed pelleting, the glue was sprayed onto the surface of the seeds using a sprayer model, Edon (ED-PDS1820 made in China); then the powdered fillers were added to the seeds repeatedly, based on the treatments, until the desired size was reached. In this experiment, Merck's gum arabic (GA) with a bulk density of 400 kg m⁻³, Merck's selenium dioxide (SD) with a density of 3.95–4.81 g cm⁻³ at 20°C–25°C, Merck's carboxymethylcellulose (CMC), and Merck's carboxymethylcellulose were used as binders, and powdered filler materials Merck's calcium sulphate (CS), Merck's zeolite (Z), Merck's talc (T), Merck's calcium carbonate (CC) and Merck's bentonite (B) were used as fillers that were purchased from Sinato Co. (Shiraz, Iran). A hot air blower model SY-300GOLD made in China was used to dry seed pellets. During the drying of the pelleted seeds, the air temperature was maintained at around 30°C.

The seed moisture was determined before and after the pelleting process. The initial moisture content of the samples was measured in an electric oven (at a temperature of 103°C ± 2°C for 17 ± 1 h) using the following formula (Hay et al. 2023).

$$MC = \frac{(W_1 - W_2)}{W_2} * 100$$

where MC moisture content on dry basis (%); W_1 mass of seed before oven drying (g) and W_2 mass of seed after oven drying (g).

The binder included gum arabic (GA), selenium dioxide (SD) and carboxymethylcellulose (CMC). The fillers used included calcium sulphate (CS), zeolite (Z), talc (T), calcium carbonate (CC) and bentonite (B). That was purchased directly or indirectly from a Merck factory. The first experiment was conducted as a factorial experiment based on a randomised complete block design (RCBD) with four replications. The treatments included a binder at 13 levels:

1. Control (seed-free binder)
2. GA₁ (20 g gum arabic per 10 g seed⁻¹)
3. GA₂ (30 g gum arabic per 10 g seed⁻¹)
4. GA₃ (40 g gum arabic per 10 g seed⁻¹)
5. GA₄ (50 g gum arabic per 10 g seed⁻¹)
6. SD₁ (20 g selenium dioxide per 10 g seed⁻¹)
7. SD₂ (30 g selenium dioxide per 10 g seed⁻¹)
8. SD₃ (40 g selenium dioxide per 10 g seed⁻¹)
9. SD₄ (50 g selenium dioxide per 10 g seed⁻¹)
10. CMC₁ (20 g carboxymethylcellulose per 10 g seed⁻¹)
11. CMC₂ (30 g carboxymethylcellulose per 10 g seed⁻¹)
12. CMC₃ (40 g carboxymethylcellulose per 10 g seed⁻¹)
13. CMC₄ (50 g carboxymethylcellulose per 10 g seed⁻¹)

and filler at five levels

1. Control (seed-free filler)
2. CS + Z (30 g calcium sulphate + 100 g zeolite per 10 g seed⁻¹)
3. CS + T (30 g calcium sulphate + 100 g talc per 10 g seed⁻¹)
4. CS + CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹)
5. CC + B (200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹)

Before the experiment initiation, the pots were filled with 1 kg of a mixture of sterilised soil and sand, in a 5:2 ratio. The soil texture was clay-loam, with the other characteristics of the soil presented in Table 1. In each pot, 10 seeds were sown, and every five pots constituted one treatment. The plants were grown in a greenhouse with day/night temperatures of 25°C/18°C (16 h/8 h).

TABLE 1 | Some physical and chemical characteristics of the soil used in the experiment pots.

pH	EC (dS m ⁻¹)	Mn (mg kg ⁻¹)	K (mg kg ⁻¹)	P (mg kg ⁻¹)	N (%) experimental	Fe (mg kg ⁻¹)	ZN (mg kg ⁻¹)
7.54	0.65	3.2	266	10	0.2	2.44	2

2.1.3 | Data Collection

2.1.3.1 | Emergence Percentage (EP) and Emergence Rate (ER). The emergence percentage and emergence rate were calculated using the following formulas (Beauchamp and Fridovich 1971).

$$EP = \text{Emerged seedling} \times 100 / n \quad (1)$$

$$MTE = \Sigma T_i N_i / \Sigma N_i \quad (2)$$

$$ER = 1 / MT \quad (3)$$

where EP represents the emergence percentage; n is the number of seeds planted in each plot; MTE denotes the mean time of emergence; T_i refers to the number of seeds emerging per day; N_i represents the total seed emergence on each measurement day and ER shows the emergence rate.

2.1.3.2 | Leaf Area (LA). At the end of the experiment, all leaves were separated from the shoot, and leaf area measurements were made using a one-meter leaf area meter, model MK2 (Delta Company, Cambridge, UK).

2.1.3.3 | Shoot and Root Length (cm). At the end of the experiment, all leaves were separated from the shoot, and shoot lengths (from the plant collar to the tip of the shoot) and root length (from the collar of the plant to the end of the main root) were measured with a ruler to an accuracy of 1 mm. The average shoot and root sizes were recorded for each treatment and replicate.

2.1.3.4 | Plant Weight Vigour Index (PWVI). These indices are used to assess seed vigour by combining germination percentage with seedling growth parameters. The PLVI and PWVI were calculated using the following formulas (Nautiyal et al. 2002).

$$PWVI = (RDW + SDW) \times EP \quad (4)$$

RDW represents root dry weight (g); SDW denotes shoot dry weight (g) and EP stands for emergence percentage, respectively.

2.1.3.5 | SPAD Index. The SPAD index was measured on the fully expanded third leaf from the top between 10:00 and 12:00 a.m. by using a SPAD chlorophyll meter (Minolta SPAD-502, Tokyo, Japan).

2.1.3.6 | Leaf Chlorophyll Content. Fresh leaf samples (1g) were crushed with 15 mL of 80% acetone, and the supernatant was collected after centrifugation at 3000 rpm for 15 min. The extract was then diluted to 25 mL using 80% acetone. The

leaf extract absorption was measured using a spectrophotometer (20-120-UV model, Japan) at 645 and 663 nm. The chlorophyll content was calculated using the following equation:

$$\text{Chlorophyll content (mg g}^{-1} \text{ FW)} = \frac{(20.2 (A) + 8.02 (B) \times V)}{(W \times 1000)} \quad (5)$$

where A and B are absorptions at 645 and 663 nm, respectively; V displays the final volume of the extract and acetone and W demonstrates fresh leaf weight (Kangsopa et al. 2023).

2.1.3.7 | Leaf Relative Water Content (RWC). Leaf relative water content reflects the current water content of a leaf relative to its maximum water-holding capacity at full turgidity. It is a widely used parameter to assess the water status of plant leaves under stress. The RWC was calculated using the following equation:

$$RWC = \frac{(FW - DW)}{(TW - DW)} * 100 \quad (6)$$

where FW is the fresh weight of the leaf samples, DW is the dry weight of the leaf samples after drying at 70°C for 48 h and TW is the turgid weight of the leaf samples.

The turgid weight was obtained by soaking the leaf samples in distilled water for 4 h until they were fully hydrated.

2.1.3.8 | Leaf Carotenoid Content. Leaf carotenoids were calculated using Arnon's method (Arnon 1967). The leaf samples were first extracted in methanol following the protocol described by Bahraminejad et al. (Bahraminejad et al. 2008).

2.1.3.9 | Physical Properties of Canola Seeds

2.1.3.9.1 | Sphericity (%). The sphericity of pelleted seed was calculated using the following equation (Mohsenin 1978).

$$\text{Sphericity} = \frac{(LBT)^{1/3}}{L} \quad (7)$$

where L is length(mm), B is width(mm) and T is thickness(mm).

2.1.3.9.2 | Fragmentation Test. For a measure of fragmentation test, four replications of 50 seeds in a petri dish were shaken for 1 min by a shaker (model Model VSS-8, India). Then the total number of cracked or broken pellets was counted (Peske and Novembre 2011).

2.1.3.9.3 | Dissolution Time (s). For easement of dissolution time, 50 randomly selected pelleted seeds were dropped in

water one by one. The time taken to dissolve the seeds in water was recorded (Doğan 2005).

2.1.3.9.4 | Pelletisation Efficiency (%). For the measure of (PE), one hundred pelleted canola seeds were randomly selected after treatment. All pellets were soaked one by one in water to separate the seed from the pelleted material; then PE was calculated using the following equation (Baladhiya et al. 2011).

$$PE(\%) = \frac{\text{Number of pellets containing seed}}{\text{Number of pellets prepared}} * 100 \quad (8)$$

2.2 | Experiment 2: In Vitro Evaluation of the Antifungal Potentials of Medicinal Plant Extracts

The second experiment aimed to introduce a medicinal plant extract instead of a natural fungicide to supplement the pelleted seeds obtained from the first experiment, to reduce the incidence of Rhizoctonia disease. The second experiment was conducted as a factorial experiment arranged in a completely randomised design (RCD) with four replications in the research laboratory of the College of Agriculture, Shiraz University, in 2024. The treatments included medicinal plant extracts at four levels (*T. vulgaris*, *Lavandula officinalis*, *C. verum* and *S. rosmarinus*) and extract concentrations at five levels (0, 500, 1000, 1500 and 2000 ppm). The medicinal plant extracts were prepared using the method described by Tekeli et al. (2011). This experiment investigated the effects of different concentrations (0, 500, 1000, 1500 and 2000 ppm) of *T. vulgaris*, *L. officinalis*, *C. verum* and *S. rosmarinus* plant extracts on the radial growth of *R. solani* and the percent inhibition (PI) in the potato dextrose agar (PDA) culture medium. A 7-day-old disc of blank paper of the pathogenic fungus was placed at the center of a petri dish, and the mycelium diameter was measured until the 5th day (Yanar et al. 2011). Blank paper discs were treated with AG₂₋₂ of *R. solani* and maintained at a temperature of 25°C. The isolate was sourced from the Fungal Collection at the Plant Protection Department, School of Agriculture, Shiraz University, Shiraz, Iran. For more details see the [Supporting Information](#).

2.2.1 | Percent Inhibition

The antifungal activity of plant extract samples on radial mycelium growth was calculated using the following equation (Sehajpal et al. 2009; Dissanayake and Kumari 2012).

$$PI(\%) = \frac{(DC - DT)}{DC} * 100 \quad (9)$$

where PI, DC and DT are the percent inhibition and diameters of the radial mycelia in the control sample and those treated with the plant extracts, respectively.

2.2.1.1 | *Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus* Extraction. Extraction is carried out using a methanol 99.99% (Pars Chemical Company, Shiraz, Iran) solvent. Five

grams of dry plant material are weighed and placed in paper bags made of filter paper. The sample is placed in a Soxhlet tank, and 250 mL of methanol solvent is poured into the flask, which is evaporated by the heat of the solvent and poured onto the sample. This cycle is repeated when the Soxhlet tank is full. The methanol solvent is returned to the flask through a thin glass siphon, and the cycle is completed. The extraction process with methanol solvent continues for 4 h. Then, the methanol containing the extracted materials is removed by a rotary evaporator (Arnon 1967) *T. vulgaris*, *L. officinalis* and *S. rosmarinus* were obtained from the medicinal plant's cultivation farm of Zar Giah Co., Firoozabad, Iran, with a temperate climate. And *C. verum* was purchased from Giah Cala Co., Shiraz, Iran.

2.3 | Experiment 3: Greenhouse Evaluation of the Antifungal Potential of Plant Extracts

The 3rd Experiment was conducted in a factorial experiment based on a randomised complete design (RCD) with four replications at the research greenhouse, after screening the antifungal plant extract treatments that were used in the second experiment in 2024. Treatments included seed pelleted seeds with the superior treatment of the first experiment CS + CC (200 g/10 g⁻¹ + 50 g/10 g⁻¹) + CMC₂ (30 g/10 g⁻¹) with the addition of four medicinal plant extracts (*T. vulgaris*, *L. officinalis*, *C. verum* and *S. rosmarinus*) and five concentrations (0, 500, 1000, 1500 and 2000 ppm). Before the experiment initiation, the pots were filled with 1 kg of a mixture of sterilised soil and sand, a 5:2 ratio. The soil in the pots was inoculated with uncolonized wheat grains at a rate of 2.5 g per kg of soil. The characteristics of the soil are presented in Table 1. Canola seeds were surface disinfected by submerging them in 70% ethanol for 3 min (with agitation), followed by a 2-min soak (with agitation) in a 0.6% sodium hypochlorite solution. In each pot, 10 seeds were sown. To prepare the inoculum, 50 g of wheat seeds were placed in a 500 mL flask. The seeds were rinsed twice with distilled water and then left to soak in it for 24 h. The flask was autoclaved three times at 121°C for 20 min, with a 24-h interval between each process. After sterilisation, five mycelium plugs were added to the flask. These were taken from seven-day-old *R. solani* colonies that had been grown on PDA. The flask was then incubated at room temperature (25°C) for 21 days. This duration was chosen to allow sclerotia formation. At the end of the 21-day incubation period, sclerotia production was confirmed. Potato dextrose agar plugs were added to the sterilised wheat seeds to serve as the control (Sabahi et al. 2023).

2.4 | Statistical Analysis

Before the analysis, the normality of the data distribution was verified using the Kolmogorov–Smirnov test with SPSS software (version 10.0; IBM, Armonk, New York, NY, USA). The data were then analysed using SAS statistical software (version 9.3; SAS Institute Inc., Cary, NC, USA) after ensuring the homogeneity of variances. Significant differences were identified using Duncan's Multiple Range Test (DMRT) at the levels of $p < 0.05$ and $p < 0.01$. The figures were created using Excel (Microsoft Inc., Chicago, IL, USA).

3 | Results and Discussion

3.1 | Experiment 1: Effects of Binder and Filler Treatments on Emergence Quality and Early Growth of Canola

The analysis of variance (ANOVA) showed that the treatments (binder and different combinations of fillers) significantly influenced the emergence and physiological-measured traits of the canola plants (Tables 2 and 3).

3.1.1 | Emergence Percentage (EP)

The type of binder had a significant effect on emergence percentage (Table 2). The seed filmed with CMC₂ showed the highest emergence percentage (Figure 1). Other researchers reported that the use of CMC in seed pelleting has been shown to improve the overall emergence rates (Doğan 2005). CMC acts as a hydrophilic polymer that retains moisture, facilitating better water uptake by seeds. This increased hydration can lead to quicker and more uniform germination (Baladhiya et al. 2011).

The percentage of emergence was significantly affected by the filler used for the seeded pelleting (Table 2). Seeds pelleted with CS+CC (200g calcium sulphate + 50g calcium carbonate) with a slope of 56.99 emerged faster than other treatments and reached the peak earlier than other treatments (Table 4, Figure 2). Similar results have been reported regarding the

effect of seed pelleting on the number of emergences in lettuce (*Lactuca sativa*) (Colla et al. 2015). The presence of both calcium compounds aids in improving the water-holding capacity of the soil. CaCO₃ can help buffer soil pH, while CaSO₄ contributes to soil structure, enhancing moisture retention around the seed (Osman 2012).

The interaction between binder and filler significantly affected the EP (Table 2). Seed pelleting increased the EP, with the highest value (97%) observed for seeds pelleted with a combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹) and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹). The seeds pelleted with combinations of CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹) and CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹) had a significant effect on emergence percentage (Table 5). The slope of the regression lines for these treatments represented that the combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹) yielded the highest constant and the highest positive trend for emergence percentage (Table 6, Figure 3). This finding contrasts with the results reported by Buakaew and Siri (Buakaew and Siri 2018), who found a decrease in germination of 11% when using CC and Z for seed pelleting. Other researchers have reported that seeds pelleted with different matrix materials, such as CS+Z, CS+pumice, CC+B and CS+T, show slightly delayed emergence compared to non-pelleted seeds under greenhouse conditions (Sharavdorj et al. 2022).

TABLE 2 | Analysis of variance emergence percentage, emergence rate, leaf area, shoot length, root length, plant length vigour index, root value, shoot dry weight, root dry weight and plant weight vigour index as affected by filler and binder.

Source	df	EP	ER (seed day ⁻¹)	LA (cm ²)	RV (cm ²)	SDW (g)	RDW (g)	PWVI
Binder (A)	12	8244.86**	0.003**	0.19**	0.15**	0.011**	0.005**	495.99**
Filler (B)	4	10002.99**	0.006**	0.74**	0.52**	0.009**	0.026**	582.73**
A*B	48	1169.96**	0.001**	0.11**	0.06ns	0.001**	0.001**	59.78**
Error	195	53.88	0.0004	0.03	0.03	0.0005	0.0003	10.78
CV%		11.85	17.14	5.57	27.26	21.06	17.62	25.90

Abbreviations: EP=emergence percentage, ER=emergence rate, LA=leaf area, PWVI=plant weight vigour index, RDW=root dry weight, RV=root value, SDW=shoot dry weight.

** and *Significant at the 1%, significant at the 5% probability level, and not significant.

TABLE 3 | Analysis of variance of SPAD index, relative water content, chlorophyll *a* content, chlorophyll *b* content and carotenoid content as affected by filler and binder.

Source	df	SPAD	RWC	Ch <i>a</i> (mg g ⁻¹ FW)	Ch <i>b</i> (mg g ⁻¹ FW)	Ca (u mg ⁻¹ protein)
Binder(A)	12	136.11**	233.93**	0.04ns	0.03ns	0.18**
Filler(B)	4	169.62**	371.37**	0.81**	0.12**	0.49**
A*B	48	41.50**	103.54**	0.09ns	0.03**	0.09**
Error	195	7.66	30.01	0.05	0.01	0.03
CV%		8.53	6.39	16.35	18.94	12.82

Abbreviations: Ca=carotenoid content, Ch *a*=chlorophyll *a* content, Ch *b*=chlorophyll *b* content, RWC=relative water content, SPAD=SPAD index.

** and *Significant at the 1%, significant at the 5% probability level, and not significant.

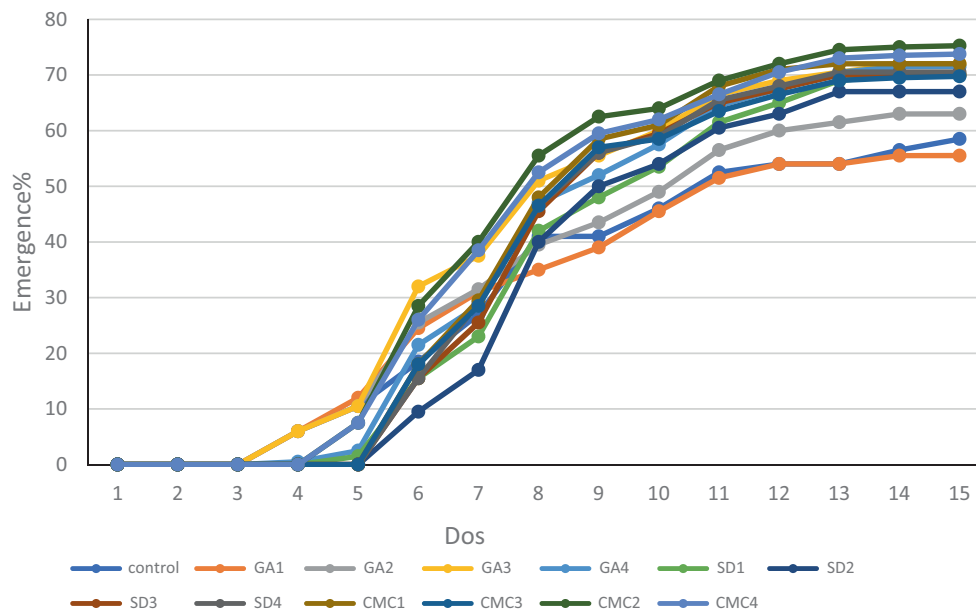


FIGURE 1 | Canola seed emergence responds to kinds of binders. CMC₁ = 20 g carboxymethylcellulose per 10 g seed⁻¹, CMC₂ = 30 g carboxymethylcellulose per 10 g seed⁻¹, CMC₃ = 40 g carboxymethylcellulose per 10 g seed⁻¹, CMC₄ = 50 g carboxymethylcellulose per 10 g seed⁻¹, DOS = day after sowing, control₁ (seed free of binder), GA₁ = 20 g gum arabic per 10 g seed⁻¹, GA₂ = 30 g gum arabic per 10 g seed⁻¹, GA₃ = 40 g gum arabic per 10 g seed⁻¹, GA₄ = 50 g gum arabic per 10 g seed⁻¹, SD₁ = 20 g selenium dioxide per 10 g seed⁻¹, SD₂ = 30 g selenium dioxide per 10 g seed⁻¹, SD₃ = 40 g selenium dioxide per 10 g seed⁻¹, SD₄ = 50 g selenium dioxide per 10 g seed⁻¹.

TABLE 4 | Logarithmic model of the emergence percentage of pelleted seeds with different kinds of filler.

Kind of pelleting	Emergence percentage	Equation	Slope	R ²
Control	73.21 ^b	$Y = 56.23\text{Ln}(x) - 70.85$	56.23	0.96
CS + Z	67.69 ^c	$Y = 49.43\text{Ln}(x) - 63.31$	49.43	0.95
CS + T	56.92 ^d	$Y = 42.61\text{Ln}(x) - 55.26$	42.61	0.94
CS + CC	80.8 ^a	$Y = 56.99\text{Ln}(x) - 63.30$	56.99	0.95
CC + B	42.21 ^e	$Y = 28.35\text{Ln}(x) - 38.54$	28.35	0.96

Note: Means followed by the same letter in each column were not different by Duncan's multiple range test ($p \leq 0.05$), control (seed free of binder), CMC₁ = 20 g carboxymethylcellulose per 10 g seed⁻¹, CMC₂ = 30 g carboxymethylcellulose per 10 g seed⁻¹, CMC₃ = 40 g carboxymethylcellulose per 10 g seed⁻¹, CMC₄ = 50 g carboxymethylcellulose per 10 g seed⁻¹, filler material: control₂ (seed free of filler), CS + Z = 30 g calcium sulphate + 100 g zeolite per 10 g seed⁻¹, CS + T = 30 g calcium sulphate + 100 g.

3.1.2 | Emergence Rate (ER)

The interaction between binder and filler significantly affected the ER (Table 2). Seed pelleting increased the ER with the highest value (0.18 seeds per day) observed for seed pelleted with a combination of CS + CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹), and CMC₂ (30 g carboxymethylcellulose per 10 g seed⁻¹). The lowest ER (0.07 seeds per day) was observed for seeds pelleted with a combination of CC + B (200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹) + GA₄ (50 g gum arabic per 10 g seed⁻¹) (Table 5). Seedling ER response to pelleting can vary among species (Ritchie et al. 2020). Other researchers have reported that the emergence has been 3.1 days faster for pelleted seeds, but the final emergence has not been significantly different (Pedrini et al. 2023). The use of CMC in seed pelleting did not have an inhibitory effect on the ER of seeds (de Camargo et al. 2017). Moreover, the combination of

CMC and CS has been found to improve the ER (Kangsopa and Siri 2015).

3.1.3 | Leaf Area

The LA was also significantly affected by the interaction of binder and filler (Table 2). Seed pelleting increased the LA, with the maximum value (3.94) observed for the same combination of CS, CC and CMC₂. The minimum LA (2.96) was observed for the control treatment or seeds pelleted with a combination of CC + B (200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹) + GA₄ (50 g gum arabic per 10 g seed⁻¹) (Table 5, Figure 4). Similar results have been reported regarding the effect of seed pelleting on the number of leaves in winter wheat (Colla et al. 2015), and LA in sunflower (Narayanan et al. 2011). Another study on soybeans has found that seeds pelleted with CMC and a filler result

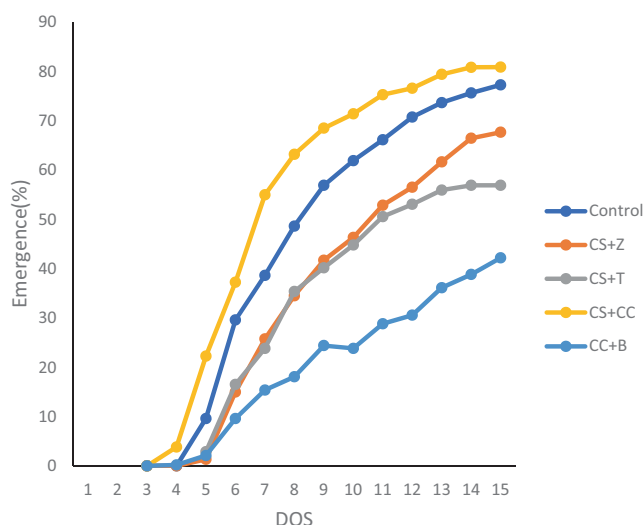


FIGURE 2 | Canola seed emergence responses to kinds of filler. CC+B=200g calcium carbonate + 50g bentonite per 10g seed⁻¹, CS+CC=200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹, CS+T=30g calcium sulphate + 100g talc per 10g seed⁻¹, CS+Z=30g calcium sulphate + 100g zeolite per 10g seed⁻¹, DOS=day after sowing, filler material: Control₂ (seed free of filler).

in higher leaf numbers per plant and higher LA ratios compared to other treatments (Rathod and Jadhao 2006). Improved root development from seed pelleting leads to better nutrient absorption by the foliage, resulting in faster growth and more leaves.

3.1.4 | Root Value

The root value was significantly affected by the interaction between the binder and filler (Table 2). Comparing the mean values, it was observed that seed pelleting increased the root value. The highest root value (1.35) was recorded in seeds pelleted with a combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹). In contrast, the lowest root value (0.297) was observed in non-pelleted seeds with a filler combination of CS+T (30g calcium sulphate + 100g talc per 10g seed⁻¹), and SD₃ (40g selenium dioxide per 10g seed⁻¹) (Table 5, Figure 4). Root parameters like root length are important indicators of a plant's ability to explore the soil and acquire resources. Previous studies have shown that seed pelleting can significantly enhance root development, including deep root growth and lateral root formation (Li et al. 2024). For instance, in rice, seed pelleting with NH₄NO₃ has improved root architecture by stimulating various radicular parameters, including root length, surface area, volume and number of tips (Blunk et al. 2019). The observed increase in root value with seed pelleting can be attributed to the beneficial effects of pelleting components. Calcium carbonate is essential for plant growth, particularly for root development and functioning, as it is involved in cell division, cell elongation and cell membrane integrity. It is also used as a fertiliser, providing calcium to plants, which is crucial for cell wall development, root growth and nutrient uptake (Sharavdorj et al. 2022). Seed pelleting with calcium oxide (CaO) facilitates better water uptake and nutrient availability, promoting stronger root growth during early development (Javed and Afzal 2018).

3.1.5 | Plant Weight Vigour Index

The interaction between the binder and filler significantly affected the plant weight vigour index (Table 2). Comparing the mean values, it was observed that seed pelleting increased the PWVI. The highest plant weight vigour index (26.67) was recorded in seeds pelleted with a combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹). The increase in the plant weight vigour index was primarily due to the increase in the shoot dry weight, which reached its highest value (0.33361 g) in this treatment (Table 5). Additionally, the root dry weight attained its highest value (0.05630 g) in this treatment (Table 5). In contrast, the lowest plant weight vigour index (1.48) was observed in the treatment with calcium sulphate + zeolite (30g calcium sulphate + 100g zeolite per 10g seed⁻¹) and the control (seed free of binder) (Table 5). Other researchers found that lettuce seeds pelleted with 0.12 and 0.24 g of NH₄NO₃ increased shoot and root dry weights significantly compared to non-pelleted seeds under laboratory conditions. Other researchers have also reported that the combination of calcium sulphate with zeolite, pumice, or diatomaceous earth shows a significant increase in shoot and root dry weights (Pierce et al. 1999). The improved shoot and root dry weights from seed pelleting are likely due to the nutrients and compounds added to the pellet, which can stimulate early seedling growth and development (Paravar et al. 2023).

3.1.6 | SPAD Index

The interaction between binder and fillers significantly affected the SPAD index (Table 3). A comparison of the averages showed that seed pelleting increased the SPAD index with the highest value (41.03) observed in seeds pelleted with the combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹). In contrast, the lowest SPAD index (10) was observed in seeds pelleted with CC+B (200g calcium carbonate + 50g bentonite per 10g seed⁻¹) + SD₃ (40g selenium dioxide per 10g seed⁻¹) (Table 7). Other researchers have reported that the SPAD index is significantly higher by approximately 10% in coated compared to uncoated wheat seeds (Anbarasan et al. 2016). However, the response of the SPAD index to seed pelleting has been found to vary among species (Colla et al. 2015). Some studies have indicated that seed pelleting with CS and CC does not have a direct effect on the SPAD index (Kangsopa et al. 2023; Mei et al. 2017). CS-based pellet matrix may promote seedling growth and improve overall plant health, leading to higher SPAD readings. Pelleting via enhanced nutrient availability contributes to increased SPAD values by promoting leaf greenness and overall plant health (Asagi et al. 2008).

3.1.7 | Leaf Carotenoid, Chlorophyll *a* and Chlorophyll *b* Contents

The interaction between binder and filler significantly affected the leaf carotenoid, chlorophyll *a* and chlorophyll *b* contents (Table 3). Seed pelleting improved the carotenoid, chlorophyll *a* and chlorophyll *b* levels with the highest values (1.84, 1.79 and

TABLE 5 | Effect of filler and binder on emergence percentage, emergence rate, leaf area, shoot length, root length, index content, root value, shoot dry weight, root dry weight, plant weight, vigour index, SPAD index, relative water, chlorophyll *a* content, chlorophyll *b* content and carotenoid content.

Filler	Binder													
	Control ₁	GA ₁	GA ₂	GA ₃	GA ₄	SD ₁	SD ₂	SD ₃	SD ₄	CMC ₁	CMC ₂	CMC ₃	CMC ₄	Mean
<i>Emergence percentage</i>														
Control ₂	73.21 ^{bc} ± 5.0	86.6 ^{de} ± 9.4	90 ^{cd} ± 8.1	90 ^{cd} ± 8.1	85 ^{bc} ± 12.9	66.6 ^{cd} ± 4.7	13.33 ^{vw} ± 4.7	17.5 ^{xy} ± 9.5	73.38 ^{bc} ± 4.7	93.33 ^{ab} ± 4.7	93.8 ^{ab} ± 8.3	82.5 ^c ± 9.5	56.67 ^{xy} ± 4.7	72.17 ^b
CS+Z	66.6k ^{cd} ± 4.7	90 ^{cd} ± 1.2	87.5 ^{cd} ± 9.5	83.3 ^{cd} ± 4.7	76.6 ^{cd} ± 4.7	20 ^{xy} ± 8.1	20 ^{xy} ± 8.1	17.6 ^{xy} ± 5.5	50 ^{xy} ± 8.16	50 ^{xy} ± 0	76.6 ^{cd} ± 12.4	85 ^{bc} ± 12.9	65 ^{cd} ± 10	57.32 ^c
CS+T	56.92 ^{xy} ± 4.7	85 ^{bc} ± 5.7	90 ^{cd} ± 8.1	83.3 ^{cd} ± 9.4	86.6 ^{cd} ± 4.7	10 ^{xy} ± 0.9	56.67 ^{xy} ± 4.7	17.5 ^{xy} ± 5	70 ^{bc} ± 8.16	70 ^{bc} ± 8.1	70.5 ^{bc} ± 8.2	27.7 ^{cd} ± 5.6	66.6 ^{cd} ± 4.7	59.03 ^c
CS+CC	85 ^{bc} ± 6.2	90 ^{cd} ± 1.3	90 ^{cd} ± 8.1	82.5 ^{cd} ± 6.4	86.7 ^{cd} ± 1.5	67.5 ^{cd} ± 9.5	63.3 ^{cd} ± 4.7	30 ^{xy} ± 8.1	75 ^{cd} ± 4.08	55 ^{xy} ± 8.1	97 ± 14.1	70.2 ^{bc} ± 1.5	75 ^{bc} ± 8.1	78.23 ^a
CC+B	42.21 ^{xy} ± 0.01	40 ^{xy} ± 14.1	25 ^{xy} ± 4.0	56.67 ^{xy} ± 4.7	60 ^{cd} ± 8.1	12.5 ^{xy} ± 5.0	12.5 ^{xy} ± 5.0	10 ^{xy} ± 0.1	18.7 ^{xy} ± 8.5	57.5 ^{xy} ± 5	34.44 ^{xy} ± 5	85 ^{bc} ± 12.2	60 ^{cd} ± 0.1	42.72 ^d
Mean	60.08 ^{de}	78.33 ^{ab}	76.50 ^{ab}	79.56 ^a	77.35 ^{ab}	36.33 ^f	33.16 ^f	18.53 ^g	57.41 ^e	70.16 ^e	79.51 ^a	74.05 ^{bc}	63.66 ^d	
<i>Emergence rate</i>														
Control ₂	0.102 ^{cd} ± 0.01	0.126 ^{cd} ± 0.01	0.116 ^{bc} ± 0.01	0.160 ^{cd} ± 1.1	0.138 ^{cd} ± 0.52	0.142 ^{cd} ± 0.01	0.096 ^{cd} ± 0.03	0.093 ^{cd} ± 0.01	0.145 ^{cd} ± 0.01	0.140 ^{cd} ± 0.01	0.141 ^{cd} ± 0.01	0.129 ^{cd} ± 0.03	0.151 ^{cd} ± 0.01	0.13 ^a
CS+Z	0.125 ^{cd} ± 0.02	0.112 ^{cd} ± 0.04	0.139 ^{cd} ± 0.01	0.136 ^{cd} ± 1.9	0.091 ^{cd} ± 0.7	0.094 ^{cd} ± 0.04	0.104 ^{cd} ± 0.02	0.106 ^{cd} ± 0.03	0.101 ^{cd} ± 0.02	0.106 ^{cd} ± 0.03	0.126 ^{cd} ± 0.02	0.125 ^{cd} ± 0.01	0.126 ^{cd} ± 0.02	0.12 ^b
CS+T	0.105 ^{cd} ± 0.03	0.133 ^{cd} ± 0.03	0.134 ^{cd} ± 0.02	0.118 ^{cd} ± 1.5	0.115 ^{cd} ± 0.3	0.092 ^{cd} ± 0.05	0.132 ^{cd} ± 0.01	0.106 ^{cd} ± 0.04	0.099 ^{cd} ± 0.04	0.137 ^{cd} ± 0.02	0.158 ^{cd} ± 0.1	0.122 ^{cd} ± 0.03	0.107 ^{cd} ± 0.04	0.12 ^b
CS+CC	0.172 ^{cd} ± 0.01	0.117 ^{cd} ± 0.02	0.123 ^{cd} ± 0.03	0.108 ^{cd} ± 1.6	0.120 ^{cd} ± 0.8	0.136 ^{cd} ± 0.3	0.112 ^{cd} ± 0.03	0.116 ^{cd} ± 0.05	0.097 ^{cd} ± 0.05	0.124 ^{cd} ± 0.04	0.185 ^{cd} ± 0.03	0.169 ^{cd} ± 0.04	0.155 ^{cd} ± 0.05	0.13 ^a
CC+B	0.132 ^{cd} ± 0.02	0.099 ^{cd} ± 0.01	0.084 ^{cd} ± 0.04	0.080 ^{cd} ± 2.0	0.074 ^{cd} ± 0.3	0.111 ^{cd} ± 0.02	0.084 ^{cd} ± 0.04	0.100 ^{cd} ± 0.06	0.074 ^{cd} ± 0.03	0.130 ^{cd} ± 0.05	0.151 ^{cd} ± 0.01	0.105 ^{cd} ± 0.05	0.136 ^{cd} ± 0.06	0.10 ^c
Mean	0.117 ^{cd}	0.117 ^{cd}	0.119 ^{cd}	0.121 ^{cd}	0.108 ^{cd}	0.115 ^{cd}	0.106 ^{cd}	0.104 ^{cd}	0.103 ^{cd}	0.127 ^{cd}	0.152 ^a	0.130 ^{cd}	0.135 ^b	
<i>Leaf area</i>														
Control ₂	3.39 ^{bc} ± 0.1	3.36 ^{cd} ± 0.2	3.51 ^{cd} ± 0.1	3.24 ^{cd} ± 0.1	3.21 ^{cd} ± 0.0	3.70 ^{cd} ± 0.2	3.13 ^{cd} ± 0.01	3.70 ^{cd} ± 0.2	3.33 ^{cd} ± 0.1	3.64 ^{cd} ± 0.2	3.36 ^{cd} ± 0.1	3.42 ^{cd} ± 0.2	3.50 ^{cd} ± 0.1	3.42 ^b
CS+Z	3.04 ^{cd} ± 0.1	3.38 ^{cd} ± 0.3	3.66 ^{cd} ± 0.2	3.31 ^{cd} ± 0.2	3.40 ^{cd} ± 0.2	3.22 ^{cd} ± 0.02	3.39 ^{cd} ± 0.1	3.40 ^{cd} ± 0.2	3.35 ^{cd} ± 0.1	3.42 ^{cd} ± 0.3	3.19 ^{cd} ± 0.01	3.38 ^{cd} ± 0.2	3.41 ^{cd} ± 0.3	3.35 ^b
CS+T	3.15 ^{cd} ± 0.1	3.30 ^{cd} ± 0.1	3.29 ^{cd} ± 0.1	2.96 ^{cd} ± 0.1	3.55 ^{cd} ± 0.3	3.27 ^{cd} ± 0.02	3.43 ^{cd} ± 0.2	3.33 ^{cd} ± 0.02	3.75 ^{cd} ± 0.2	3.83 ^{cd} ± 0.1	3.42 ^{cd} ± 0.1	3.32 ^{cd} ± 0.1	3.31 ^{cd} ± 0.1	3.38 ^b
CS+CC	3.42 ^{cd} ± 0.02	3.40 ^{cd} ± 0.0	3.65 ^{cd} ± 0.2	3.64 ^{cd} ± 0.1	3.61 ^{cd} ± 0.1	3.89 ^{cd} ± 0.1	3.54 ^{cd} ± 0.1	3.69 ^{cd} ± 0.01	3.90 ^{cd} ± 0.2	3.53 ^{cd} ± 0.1	3.94 ^{cd} ± 0.0	3.58 ^{cd} ± 0.02	3.58 ^{cd} ± 0.1	3.64 ^a
CC+B	3.22 ^{cd} ± 0.03	3.14 ^{cd} ± 0.0	3.39 ^{cd} ± 0.3	3.60 ^{cd} ± 0.2	3.29 ^{cd} ± 0.1	3.70 ^{cd} ± 0.1	3.47 ^{cd} ± 0.1	3.34 ^{cd} ± 0.01	3.39 ^{cd} ± 0.1	3.53 ^{cd} ± 0.3	3.12 ^{cd} ± 0.1	3.38 ^{cd} ± 0.5	3.40 ^{cd} ± 0.1	3.38 ^b
Mean	3.24 ^f	3.32 ^{cd}	3.50 ^{cd}	3.35 ^{cd}	3.41 ^{cd}	3.56 ^{cd}	3.39 ^{cd}	3.49 ^{cd}	3.54 ^{ab}	3.40 ^{cd}	3.59 ^a	3.42 ^{cd}	3.44 ^{cd}	
<i>Root value</i>														
Control ₂	0.61 ^{cd} ± 0.01	0.80 ^{cd} ± 0.1	0.64 ^{cd} ± 0.6	0.76 ^{cd} ± 0.1	0.80 ^{cd} ± 0.01	0.68 ^{cd} ± 0.1	0.50 ^{cd} ± 0.01	0.80 ^{cd} ± 0.01	0.56 ^{cd} ± 0.1	0.65 ^{cd} ± 0.1	0.63 ^{cd} ± 0.1	0.64 ^{cd} ± 0.1	0.64 ^{cd} ± 0.1	0.67 ^b
CS+Z	0.31 ^{cd} ± 0.1	0.73 ^{cd} ± 0.01	0.71 ^{cd} ± 0.1	0.73 ^{cd} ± 1	0.57 ^{cd} ± 0.02	0.46 ^{cd} ± 0.2	0.62 ^{cd} ± 0.02	0.66 ^{cd} ± 0.01	0.66 ^{cd} ± 0.2	0.67 ^{cd} ± 0.1	0.66 ^{cd} ± 0.2	0.57 ^{cd} ± 0.1	0.43 ^{cd} ± 0.2	0.60 ^c
CS+T	0.46 ^{cd} ± 0.02	0.61 ^{cd} ± 0.01	0.80 ^{cd} ± 0.1	0.73 ^{cd} ± 3	0.65 ^{cd} ± 0.03	0.98 ^{cd} ± 0.6	0.65 ^{cd} ± 0.03	0.297 ^{cd} ± 0.1	0.71 ^{cd} ± 0.1	0.60 ^{cd} ± 0.1	0.60 ^{cd} ± 0.3	0.73 ^{cd} ± 0.2	0.62 ^{cd} ± 0.2	0.65 ^{bc}
CS+CC	0.45 ^{cd} ± 0.03	0.80 ^{cd} ± 0.2	0.85 ^{cd} ± 0.3	0.73 ^{cd} ± 4	1.01 ^{cd} ± 0.05	0.62 ^{cd} ± 0.2	0.77 ^{cd} ± 0.04	0.80 ^{cd} ± 0.1	0.75 ^{cd} ± 0.3	0.76 ^{cd} ± 0.1	1.35 ^{cd} ± 0.5	0.81 ^{cd} ± 0.3	0.62 ^{cd} ± 0.3	0.80 ^a
CC+B	0.41 ^{cd} ± 0.04	0.60 ^{cd} ± 0.3	0.64 ^{cd} ± 0.2	0.56 ^{cd} ± 0.1	0.41 ^{cd} ± 0.01	0.40 ^{cd} ± 0.2	0.66 ^{cd} ± 0.2	0.36 ^{cd} ± 0.2	0.63 ^{cd} ± 0.2	0.50 ^{cd} ± 0.2	0.52 ^{cd} ± 0.1	0.61 ^{cd} ± 0.2	0.46 ^{cd} ± 0.1	0.52 ^d
Mean	0.45 ^e	0.71 ^b	0.83 ^a	0.71 ^b	0.69 ^{bc}	0.64 ^{cd}	0.64 ^{cd}	0.58 ^{cd}	0.66 ^{cd}	0.66 ^{cd}	0.66 ^{cd}	0.67 ^{bc}	0.55 ^{de}	

(Continues)

TABLE 5 | (Continued)

Filler	Binder													
	Control ₁	GA ₁	GA ₂	GA ₃	GA ₄	SD ₁	SD ₂	SD ₃	SD ₄	CMC ₁	CMC ₂	CMC ₃	CMC ₄	Mean
Shoot dry weight														
Control ₂	0.088 ^{u-v} ± 0.01	0.094 ^{u-v} ± 0.01	0.081 ^{r-v} ± 0.01	0.110 ^{r-v} ± 0.02	0.098 ^{u-v} ± 0.01	0.100 ^{m-u} ± 0.07	0.093 ^{n-u} ± 0.01	0.130 ^{b-m} ± 0.01	0.123 ^{d-n} ± 0.02	0.115 ^{s-q} ± 0.02	0.125 ^{s-n} ± 0.01	0.110 ^{r-v} ± 0.02	0.104 ^{r-l} ± 0.07	0.105 ^b
CS+Z	0.014 ^k ± 0.02	0.071 ^{w-y} ± 0.02	0.128 ^{c-m} ± 0.02	0.090 ^{u-v} ± 0.01	0.110 ^{r-v} ± 0.02	0.033 ^{g-w} ± 0.03	0.110 ^{d-r} ± 0.05	0.136 ^{b-r} ± 0.02	0.115 ^{s-q} ± 0.03	0.129 ^{c-m} ± 0.07	0.135 ^{b-k} ± 0.02	0.129 ^{c-m} ± 0.03	0.111 ^{r-l} ± 0.03	0.101 ^b
CS+T	0.020 ^z ± 0.04	0.117 ^{d-q} ± 0.03	0.107 ^{h-s} ± 0.03	0.103 ^{k-u} ± 0.03	0.086 ^{q-v} ± 0.03	0.103 ^{k-u} ± 0.02	0.120 ^{d-p} ± 0.07	0.108 ^{s-s} ± 0.03	0.100 ^{m-u} ± 0.04	0.140 ^{b-g} ± 0.05	0.141 ^{b-r} ± 0.03	0.122 ^{d-o} ± 0.04	0.129 ^{b-m} ± 0.02	0.107 ^b
CS+CC	0.076 ^{t-v} ± 0.05	0.140 ^{b-h} ± 0.04	0.141 ^{b-r} ± 0.03	0.113 ^{r-v} ± 0.02	0.113 ^{e-r} ± 0.04	0.133 ^{b-l} ± 0.01	0.120 ^{d-p} ± 0.08	0.136 ^{b-r} ± 0.04	0.142 ^{b-r} ± 0.02	0.135 ^{b-k} ± 0.08	0.186 ^q ± 0.04	0.147 ^{b-d} ± 0.05	0.158 ^{s-c} ± 0.04	0.134 ^s
CC+B	0.022 ^z ± 0.02	0.075 ^{t-v} ± 0.01	0.056 ^{g-w} ± 0.02	0.105 ^{r-l} ± 0.01	0.086 ^{q-v} ± 0.05	0.144 ^{b-e} ± 0.03	0.118 ^{d-q} ± 0.02	0.107 ^{b-l} ± 0.05	0.101 ^{l-u} ± 0.02	0.118 ^{d-q} ± 0.01	0.119 ^{d-q} ± 0.02	0.137 ^{b-l} ± 0.07	0.162 ^{ab} ± 0.06	0.104 ^b
Mean	0.044 ^z	0.099 ^f	0.103 ^{ef}	0.104 ^{ef}	0.099 ^f	0.103 ^{ef}	0.112 ^{d-r}	0.123 ^{b-d}	0.116 ^{s-e}	0.127 ^{b-c}	0.141 ^a	0.129 ^{b-c}	0.132 ^{ab}	
Root dry weight														
Control ₂	0.107 ^{k-u} ± 0.02	0.121 ^{r-p} ± 0.03	0.129 ^{e-r} ± 0.02	0.115 ^{z-r} ± 0.01	0.107 ^{k-u} ± 0.02	0.110 ^{r-l} ± 0.02	0.094 ^{o-v} ± 0.01	0.083 ^{b-z} ± 0.07	0.097 ^{h-y} ± 0.01	0.105 ^{k-u} ± 0.01	0.114 ^{z-s} ± 0.02	0.108 ^{k-u} ± 0.03	0.137 ^{r-l} ± 0.05	0.110 ^b
CS+Z	0.044 ^z ± 0.04	0.109 ^{l-u} ± 0.04	0.100 ^{m-x} ± 0.03	0.116 ^{z-q} ± 0.02	0.135 ^{c-j} ± 0.03	0.103 ^{b-v} ± 0.04	0.108 ^{k-u} ± 0.02	0.095 ^{s-y} ± 0.08	0.094 ^{z-z} ± 0.02	0.082 ^{u-z} ± 0.02	0.088 ^{z-z} ± 0.03	0.121 ^{f-o} ± 0.04	0.125 ^{f-m} ± 0.02	0.101 ^c
CS+T	0.050 ^z ± 0.05	0.145 ^{c-r} ± 0.05	0.131 ^{d-k} ± 0.04	0.117 ^{z-q} ± 0.03	0.105 ^{k-u} ± 0.05	0.115 ^{z-r} ± 0.07	0.101 ^{m-w} ± 0.03	0.077 ^{z-z} ± 0.02	0.111 ^{b-l} ± 0.03	0.073 ^{z-z} ± 0.06	0.124 ^{r-n} ± 0.04	0.153 ^{s-e} ± 0.05	0.105 ^{k-u} ± 0.07	0.108 ^{bc}
CS+CC	0.139 ^{s-g} ± 0.03	0.184 ^{ab} ± 0.07	0.139 ^{s-g} ± 0.05	0.139 ^{s-g} ± 0.04	0.131 ^{d-k} ± 0.06	0.115 ^{z-r} ± 0.08	0.138 ^{e-h} ± 0.04	0.123 ^{f-n} ± 0.03	0.161 ^{bc} ± 0.04	0.106 ^{k-u} ± 0.08	0.190 ^q ± 0.05	0.156 ^{cd} ± 0.07	0.139 ^{s-g} ± 0.08	0.143 ^s
CC+B	0.048 ^z ± 0.01	0.094 ^{z-r} ± 0.09	0.071 ^y ± 0.06	0.109 ^{l-u} ± 0.07	0.092 ^{q-z} ± 0.08	0.074 ^{x-z} ± 0.01	0.075 ^{w-z} ± 0.07	0.053 ^{z-o} ± 0.01	0.067 ^z ± 0.07	0.089 ^{r-z} ± 0.06	0.098 ^{m-y} ± 0.07	0.089 ^{r-z} ± 0.08	0.086 ^{r-z} ± 0.03	0.080 ^d
Mean	0.07 ^e	0.13 ^a	0.11 ^{bc}	0.12 ^{ab}	0.11 ^{bc}	0.10 ^c	0.10 ^c	0.08 ^{de}	0.10 ^c	0.09 ^d	0.12 ^{ab}	0.12 ^{ab}	0.11 ^b	
Plant weight vigour index														
Control ₂	17.64 ^{d-l} ± 0.6	17.12 ^{r-p} ± 3.2	17.65 ^{e-m} ± 10.1	18.40 ^{d-k} ± 0.4	18.05 ^{d-l} ± 0.9	2.24 ^z ± 0.3	3.76 ^z ± 5.5	3.73 ^z ± 2.0	2.24 ^z ± 0.3	13.18 ^{m-l} ± 3.7	20.56 ^{b-h} ± 3.7	16.45 ^{b-i} ± 1.5	13.92 ^{k-l} ± 6.7	12.78 ^b
CS+Z	1.48 ^z ± 0.1	17.59 ^{e-o} ± 6.5	19.22 ^{c-h} ± 3.4	6.81 ^z ± 4.9	14.61 ^{l-u} ± 2.5	7.20 ^z ± 1.0	13.72 ^{l-u} ± 1.4	5.58 ^z ± 3.3	13.35 ^{am} ± 0.8	10.77 ^{r-w} ± 0.3	12.46 ^{b-u} ± 3.9	21.60 ^{b-f} ± 0.6	13.20 ^{n-l} ± 0.3	12.12 ^b
CS+T	2.68 ^z ± 0.0	20.51 ^{b-h} ± 0.7	20.96 ^{b-g} ± 0.7	14.34 ^{d-l} ± 3.9	10.98 ^{s-w} ± 2.0	2.39 ^z ± 0.1	11.73 ^{r-v} ± 2.0	3.73 ^z ± 0.9	11.64 ^{r-v} ± 2.0	12.68 ^{b-u} ± 6.0	16.48 ^{e-q} ± 3.4	21.80 ^{b-e} ± 0.6	14.35 ^{r-l} ± 0.7	12.64 ^b
CS+CC	19.11 ^{c-l} ± 1.2	23.15 ^{s-v} ± 5.5	22.56 ^{e-d} ± 1.8	19.61 ^{b-h} ± 5.8	17.81 ^{e-m} ± 2.9	6.30 ^z ± 0.4	12.16 ^{h-v} ± 2.8	8.20 ^{r-y} ± 1.4	16.01 ^{b-r} ± 0.4	12.68 ^{b-u} ± 1.0	26.66 ^z ± 2.4	24.38 ^{ab} ± 2.4	18.60 ^{c-j} ± 2.6	17.62 ^a
CC+B	4.53 ^z ± 0.2	11.95 ^{tu} ± 0.9	4.66 ^z ± 2.9	10.20 ^{s-w} ± 5.3	10.01 ^{l-s} ± 3.4	2.26 ^z ± 0.0	2.37 ^z ± 0.5	2.10 ^{b-o} ± 0	4.63 ^z ± 1.2	14.50 ^{r-l} ± 1.2	13.14 ^{r-l} ± 10.4	13.01 ^{b-l} ± 1.5	13.20 ^{n-l} ± 0.1	8.19 ^c
Mean	9.09 ^d	18.06 ^{ab}	17.01 ^b	13.87 ^c	14.29 ^c	4.12 ^e	9.00 ^d	4.67 ^e	9.57 ^d	13.08 ^c	17.86 ^{ab}	19.45 ^a	14.65 ^c	

Note: Data represented from four replications. Means followed by the same letter in each treatment were not different by Duncan's multiple range test ($p \leq 0.05$), binder material: control₁ (seed free of binder), GA₁ = 20g gum arabic per 10g seed⁻¹, GA₂ = 30g gum arabic per 10g seed⁻¹, GA₃ = 40g gum arabic per 10g seed⁻¹, GA₄ = 50g gum arabic per 10g seed⁻¹, SD₁ = 20g selenium dioxide per 10g seed⁻¹, SD₂ = 30g selenium dioxide per 10g seed⁻¹, SD₃ = 40g selenium dioxide per 10g seed⁻¹, SD₄ = 50g selenium dioxide per 10g seed⁻¹, CMC₁ = 20g carboxymethylcellulose per 10g seed⁻¹, CMC₂ = 30g carboxymethylcellulose per 10g seed⁻¹, CMC₃ = 40g carboxymethylcellulose per 10g seed⁻¹, CMC₄ = 50g carboxymethylcellulose per 10g seed⁻¹, filler material: control₁ (seed free of filler), CS + Z = 30g calcium sulphate + 100g talc per 10g seed⁻¹, CS + T = 30g calcium sulphate + 100g talc per 10g seed⁻¹, CS + CC = 200g calcium carbonate + 50g calcium carbonate per 10g seed⁻¹, CC + B = 200g calcium carbonate + 50g bentonite per 10g seed⁻¹.

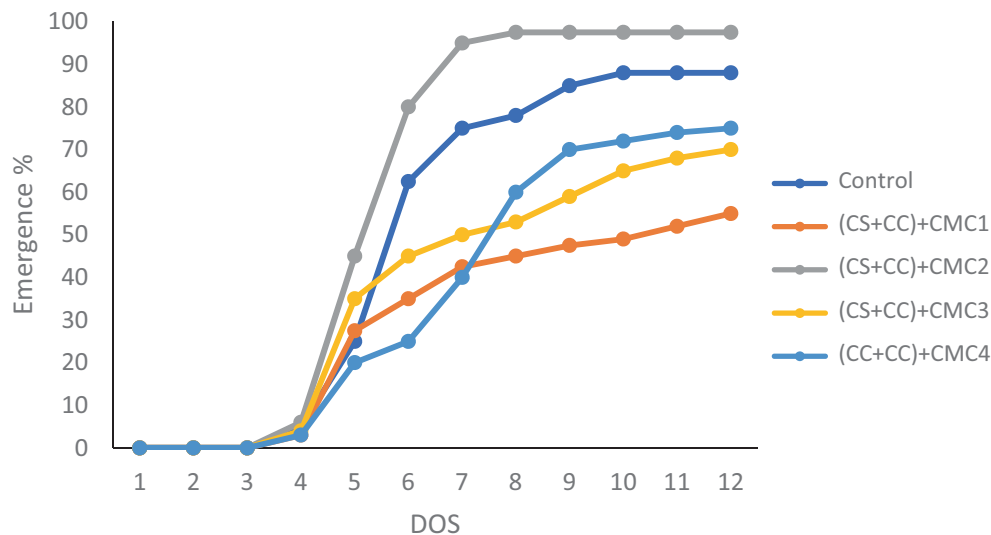


FIGURE 3 | Canola seed emergence responses to pelleted material. CC + B = 200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹, CMC₁ = 20 g carboxymethylcellulose per 10 g seed⁻¹, CMC₂ = 30 g carboxymethylcellulose per 10 g seed⁻¹, CMC₃ = 40 g carboxymethylcellulose per 10 g seed⁻¹, CMC₄ = 50 g carboxymethylcellulose per 10 g seed⁻¹, filler material: Control₂ (seed free of filler), CS + CC = 200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹, CS + T = 30 g calcium sulphate + 100 g talc per 10 g seed⁻¹, CS + Z = 30 g calcium sulphate + 100 g zeolite per 10 g seed⁻¹, DOS = day after sowing, control₁ (seed free of binder).

TABLE 6 | Logarithmic model of the emergence percentage of pelleted seeds with the combination of kinds of binder and filler.

Kind of pelleting	Emergence percentage	Equation	Slope	R ²
Control	75 ^b	$Y = 47.13\ln(x) - 28.95$	47.13	0.82
(CS + CC) + CMC ₁	55 ^c	$Y = 5.98\ln(x) - 8.89$	5.98	0.89
(CS + CC) + CMC ₂	97 ^a	$Y = 53.81\ln(x) - 30.15$	53.8	0.80
(CS + CC) + CMC ₃	70 ^{ab}	$Y = 7.59\ln(x) - 1.92$	7.59	0.91
(CS + CC) + CMC ₄	75 ^b	$Y = 35.2\ln(x) - 25.29$	38.2	0.84

Note: Means followed by the same letter in each column were not different by Duncan's multiple range test ($p \leq 0.05$), control (seed free of binder), CMC₁ = 20 g carboxymethylcellulose per 10 g seed⁻¹, CMC₂ = 30 g carboxymethylcellulose per 10 g seed⁻¹, CMC₃ = 40 g carboxymethylcellulose per 10 g seed⁻¹, CMC₄ = 50 g carboxymethylcellulose per 10 g seed⁻¹, filler material: control₂ (seed free of filler), CS + Z = 30 g calcium sulphate + 100 g zeolite per 10 g seed⁻¹, CS + T = 30 g calcium sulphate + 100 g talc per 10 g seed⁻¹, CS + CC = 200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹, CC + B = 200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹.

0.787, respectively) recorded in seeds pelleted with a combination of CS + CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹), and CMC₂ (30 g carboxymethylcellulose per 10 g seed⁻¹). In contrast, the minimum carotenoid, chlorophyll *a*, and chlorophyll *b* contents (0.70, 0.782 and 0.277, respectively) were observed in seeds pelleted with CS + Z (30 g calcium sulphate + 100 g zeolite per 10 g seed⁻¹) and GA₃ (40 g gum arabic per 10 g seed⁻¹) (Table 7). These findings are consistent with the results reported by Prakash et al. (Prakash et al. 2021), who demonstrated the positive effect of seed pelleting on carotenoid, chlorophyll *a* and chlorophyll *b* levels. The increase in chlorophyll content is likely due to improved nutrient absorption, which leads to enhanced photosynthetic activity in plants grown from pelleted seeds (Prakash et al. 2021). Additionally, other researchers have found that pelleting cucumber seeds with CS can result in higher carotenoid content compared to non-pelleted seeds (Mei et al. 2017). This is attributed to the CS-based pellet matrix promoting seedling growth and improving overall plant health, which in turn leads to higher carotenoid levels and chlorophyll content. This enhanced growth is associated with improved metabolic activity, including processes

that may indirectly affect chlorophyll synthesis and degradation during early development (Mei et al. 2017).

3.1.8 | Leaf Relative Water Content (RWC)

The interaction between binder and filler significantly affected the leaf RWC (Table 3). Comparing the mean values, it was observed that seed pelleting increased the RWC. The highest RWC (94.90) was recorded in seed pelleted with a combination of CS + CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹), and CMC₂ (30 g carboxymethylcellulose per 10 g seed⁻¹), while the control (non-pelleted) treatment had an RWC of (78.87). In contrast, the lowest leaf RWC (65.45) was observed in seeds pelleted with CS + T (30 g calcium sulphate + 100 g talc per 10 g seed⁻¹), CMC₃ (40 g carboxymethylcellulose per 10 g seed⁻¹) (Table 7). These findings are consistent with the results reported (Behboud et al. 2024), who demonstrated the positive effect of seed pelleting on leaf RWC. Other researchers have also found that the use of calcium peroxide in seed pelleting improved seed-water relations, leading to enhanced RWC of seeds (Mei et al. 2017). The increase in leaf

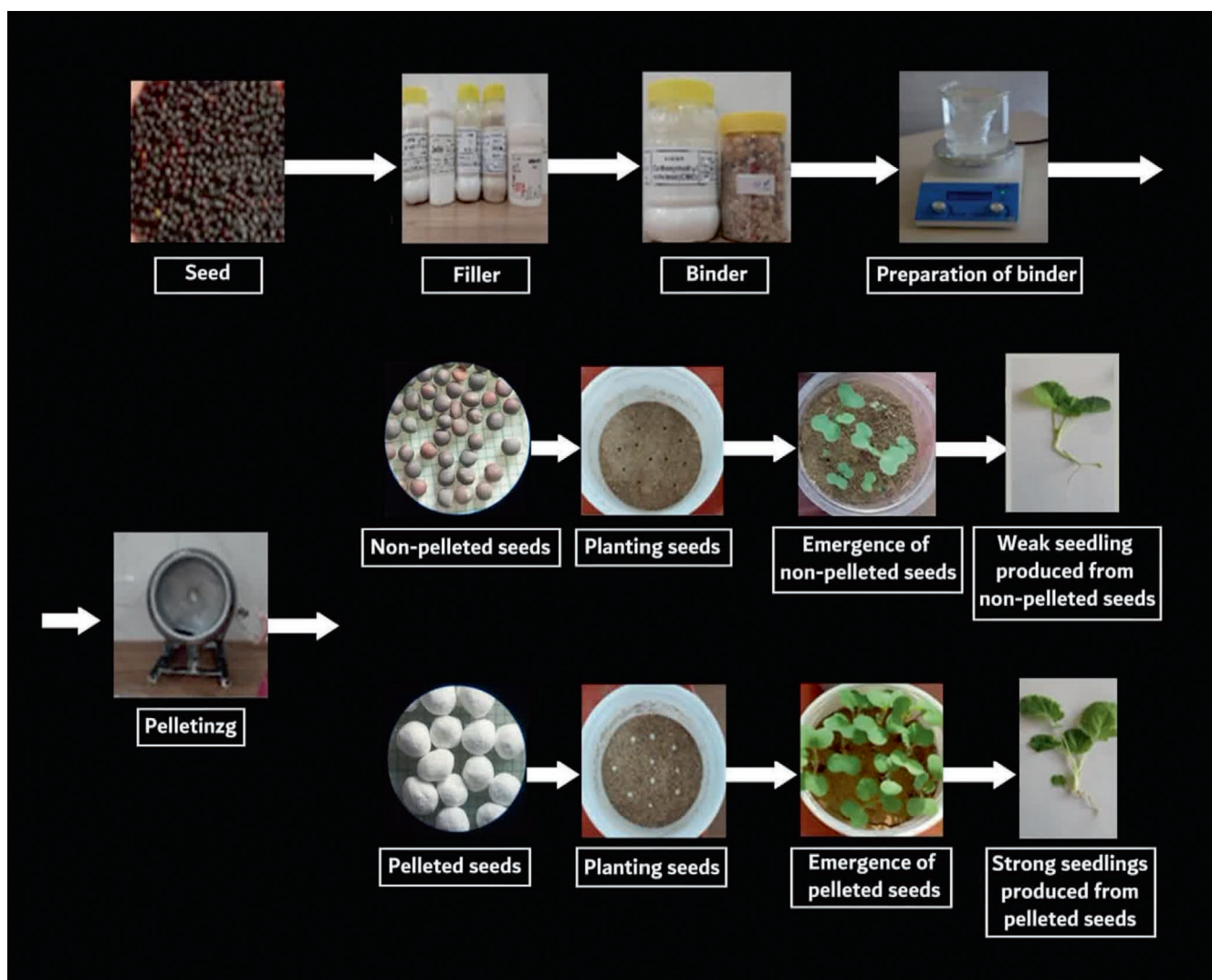


FIGURE 4 | The figure shows the first experiment protocol followed.

RWC observed in the pelleted seeds is likely due to seed coating augmenting the seedling's access to water (Kumar et al. 2021). This improved water uptake and retention can be beneficial for plant growth and development, particularly under water stress conditions. Seed-pelleting materials, such as calcium peroxide (CaO_2), enhance water absorption by increasing soil-seed contact and modifying soil properties (Chaiyasarn and Siri 2019). Calcium carbonate helps maintain adequate water availability for seeds, which is crucial for sustaining higher RWC during early growth stages (Pierce et al. 1999).

3.1.9 | Physical Properties of Canola Seeds

Physical properties include sphericity, thousand seed weight (1000-SW), fragmentation test, dissolution rate and pelletisation efficiency (PE) of pelleted canola seeds, which were calculated and furnished in Table 8.

3.1.9.1 | Sphericity. The results showed that the range of sphericity of the treatment under study was 0.93–0.99 (%). In all treatments (filler), the sphericity of plated seeds increased

with increasing binder content. The highest sphericity (0.99%) was recorded in seeds pelleted with a combination of CS+CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹) (Table 8). The sphericity measures how closely a seed's shape resembles a sphere. As the sphericity generally improves, the seed becomes more spherical. For pelleted seeds, sphericity is critical in evaluating their physical properties, as higher sphericity ensures better flowability and precision during mechanical sowing, uniform pellets improve seed placement and emergence rates, and spherical pellets improve handling and transport too (Hacıyusufoğlu and Akbaş 2019).

3.1.9.2 | Fragmentation Test. The average fragmentation number for pelleted seeds was 6–20 per 50 seeds. In all treatments (filler), the fragmentation of plated seeds decreased with increasing binder content (Table 8). The fragmentation test evaluates the physical integrity and durability of the seed coating under specific conditions. This test is essential to ensure that the coating remains intact during handling, transportation and sowing, but disintegrates appropriately to allow seed germination (Asagi et al. 2008).

TABLE 7 | Effect of filler and binder on SPAD index, carotenoid content, chlorophyll *a* content, chlorophyll *b* content, relative water content.

Filler	Binder													Mean
	Control ₁	GA ₁	GA ₂	GA ₃	GA ₄	SD ₁	SD ₂	SD ₃	SD ₄	CMC ₁	CMC ₂	CMC ₃	CMC ₄	
SPAD index														
Control ₂	41.55 ^a ±3.1	27.80 ^{b-s} ±7.0	34.68 ^{b-h} ±1.2	31.68 ^{b-o} ±2.6	31.83 ^{b-o} ±1.5	31.69 ^{b-o} ±0.7	29.21 ^{b-r} ±5.6	29.21 ^{b-r} ±5.6	34.43 ^{c-i} ±0.9	32.29 ^{c-k} ±0.6	32.87 ^{c-n} ±0.3	31.85 ^{b-o} ±2.1	34.36 ^{c-j} ±0.5	32.58 ^b
CS+Z	28.36 ^{c-s} ±2.6	32.07 ^{c-o} ±1.8	33.75 ^{c-l} ±0.9	34.62 ^{c-h} ±0.5	34.34 ^{c-i} ±0.2	30.37 ^{b-q} ±0.2	26.10 ^{b-r} ±6.5	30.74 ^{b-l} ±3.7	34.34 ^{c-i} ±0.5	32.63 ^{c-n} ±1.1	32.57 ^{b-n} ±1.7	34.66 ^{b-h} ±0.6	32.65 ^{c-n} ±3.0	32.05 ^b
CS+T	38.49 ^{ab} ±2.2	29.63 ^{m-r} ±2.7	33.69 ^{c-l} ±2.0	34.01 ^{c-l} ±1.7	32.18 ^{c-o} ±3.1	27.58 ^{b-q} ±4.2	32.63 ^{c-n} ±0.4	30.58 ^{b-q} ±5.6	35.85 ^{0-b} ±1.0	32.17 ^{c-o} ±2.3	33.37 ^{c-m} ±0.7	34.20 ^{c-k} ±0.1	33.83 ^{c-l} ±0.7	32.94 ^b
CS+CC	36.15 ^{b-e} ±1.0	33.52 ^{c-l} ±6.8	34.91 ^{b-g} ±1.3	33.45 ^{c-m} ±0.0	36.31 ^{b-d} ±4.0	31.68 ^{b-o} ±0.2	32.69 ^{c-n} ±0.1	33.62 ^{c-l} ±0.9	36.46 ^{7-b} ±2.1	33.56 ^{c-l} ±0.7	41.03 ^a ±0.5	34.94 ^{b-q} ±1.3	34.46 ^{c-l} ±2.6	34.83 ^a
CC+B	34.36 ^{c-j} ±1.4	31.16 ^{b-q} ±4.5	26.13 ^{r-s} ±2.8	30.75 ^{c-q} ±1.3	33.00 ^{c-r} ±1.8	25.07 ^b ±3.9	30.96 ^{b-q} ±0.2	10.00 ^l ±0	34.85 ^{0-b} ±2.3	32.66 ^{c-n} ±1.2	33.34 ^{c-m} ±0.8	31.65 ^{b-p} ±6.3	33.59 ^{c-l} ±2.3	29.81 ^c
Mean	36.76 ^a	30.84 ^d	32.63 ^c	32.90 ^c	33.53 ^{bc}	29.28 ^d	30.32 ^d	26.73 ^e	35.19 ^{ab}	32.68 ^c	33.66 ^{bc}	33.46 ^{bc}	33.78 ^{bc}	
Leaf relative water content (RWC)														
Control ₂	82.10 ^{b-1} ±2.3	83.41 ⁸⁻¹ ±2.5	85.05 ^{d-s} ±6.0	79.21 ^{h-u} ±7.4	81.28 ¹⁻¹ ±9.4	90.88 ^{a-g} ±4.3	88.94 ^{a-h} ±5.7	92.14 ^{a-e} ±0.6	92.62 ^{a-d} ±3.8	78.87 ^{r-u} ±4.5	85.43 ^{c-r} ±3.7	88.69 ^{a-l} ±4.2	70.03 ^{vw} ±6.4	84.72 ^b
CS+Z	84.79 ^{c-1} ±9.0	88.54 ^{a-1} ±5.1	88.02 ^{a-m} ±3.8	80.33 ⁿ⁻¹ ±1.6	85.37 ^{c-r} ±6.0	82.10 ^{b-1} ±6.6	84.80 ^{e-1} ±9.4	91.95 ^{a-f} ±3.0	91.89 ^{a-f} ±4.0	92.16 ^{a-e} ±2.5	88.18 ^{a-l} ±0.7	72.26 ^{u-w} ±13.1	80.43 ^{m-1} ±9.9	85.45 ^b
CS+T	83.39 ^{c-1} ±2.4	89.32 ^{a-b} ±3.7	87.70 ^{a-o} ±1.8	78.75 ^{v-y} ±4.8	86.58 ^{b-q} ±5.6	92.75 ^{a-c} ±3.1	87.88 ^{a-u} ±5.0	91.87 ^{a-f} ±2.9	81.04 ¹⁻¹ ±8.2	77.22 ^{xy} ±7.6	81.28 ^{c-1} ±7.6	65.44 ^w ±6.0	83.44 ⁸⁻¹ ±7.9	83.59 ^b
CS+CC	86.73 ^{b-q} ±4.4	90.70 ^{a-g} ±1.0	88.27 ^{a-k} ±2.1	81.09 ¹⁻¹ ±1.5	89.22 ^{a-b} ±2.3	92.93 ^{a-c} ±3.7	93.12 ^{ab} ±0.6	94.02 ^{ab} ±0.6	93.52 ^{ab} ±1.0	92.50 ^{a-d} ±0.6	94.90 ^a ±0.5	90.36 ^{a-g} ±3.3	88.28 ^{a-k} ±6.2	90.22 ^a
CC+B	77.53 ^{z-v} ±7.2	85.47 ^{c-1} ±3.8	80.66 ^{k-l} ±5.0	81.07 ¹⁻¹ ±1.5	84.42 ¹⁻¹ ±3.7	89.03 ^{a-b} ±2.6	90.67 ^{a-g} ±2.1	79.86 ^{o-1} ±16.5	86.59 ^{b-q} ±5.7	80.08 ^{o-1} ±3.4	80.63 ^{u-w} ±4.2	89.69 ^{a-b} ±5.0	87.10 ^{b-p} ±1.9	84.06 ^b
Mean	82.91 ^{d-f}	87.49 ^{a-c}	85.94 ^{b-d}	80.09 ^f	85.37 ^{cd}	90 ^a	89.08 ^{ab}	90.52 ^a	89.13 ^{ab}	84.17 ^{c-e}	85.53 ^{cd}	81.29 ^{cd}	81.86 ^{cd}	
Chlorophyll a														
Control ₂	1.36 ^{c-q} ±0.1	1.27 ^{f-q} ±0.3	1.45 ^{b-o} ±0.4	1.50 ^{a-k} ±0.03	1.38 ^{c-p} ±0.02	1.30 ^{e-q} ±0.1	1.49 ^{a-1} ±0.4	1.29 ^{e-q} ±0.02	1.27 ^{f-q} ±0.0	1.38 ^{c-q} ±0.3	1.46 ^{b-n} ±0.1	1.41 ^{c-p} ±0.2	1.66 ^{a-d} ±0.1	1.40 ^b
CS+Z	1.21 ^{j-q} ±0.4	1.67 ^{a-o} ±0.1	1.38 ^{c-p} ±0.4	0.78 ^t ±0.1	1.46 ^{b-m} ±0.01	1.25 ^{8-q} ±0.1	1.49 ^{a-1} ±0.2	1.18 ¹⁻¹ ±0.1	1.58 ^{e-1} ±0.2	1.59 ^{a-e} ±0.1	1.39 ^{c-p} ±0.1	1.42 ^{c-p} ±0.1	1.37 ^{c-q} ±0.3	1.38 ^b
CS+T	1.33 ^{e-q} ±0.3	1.12 ^q ±0.1	1.16 ^{m-q} ±0.1	1.45 ^{b-o} ±0.2	1.48 ^{a-m} ±0.2	1.43 ^{c-p} ±0.2	1.44 ^{c-p} ±0.02	1.50 ^{a-k} ±0.2	1.37 ^{c-q} ±0.3	1.40 ^{c-p} ±0.1	1.31 ^{e-q} ±0.2	1.35 ^{c-q} ±0.2	1.52 ^{a-1} ±0.1	1.38 ^b
CS+CC	1.52 ^{a-j} ±0.2	1.65 ^{a-d} ±0.1	1.48 ^{a-m} ±0.2	1.67 ^{a-c} ±0.7	1.77 ^{ab} ±0.1	1.50 ^{a-k} ±0.1	1.58 ^{a-1} ±0.2	1.80 ^a ±0.01	1.53 ^{a-1} ±0.2	1.51 ^{a-k} ±0.2	1.79 ^a ±0.1	1.53 ^{a-1} ±0.1	1.54 ^{a-h} ±0.1	1.60 ^a
CC+B	1.34 ^l ±0.4	1.14 ^{o-q} ±0.3	1.30 ^{1-q} ±0.2	1.37 ^{a-q} ±0.2	1.27 ^{f-q} ±0.1	1.23 ^{h-q} ±0.1	1.15 ^{a-q} ±0.03	1.28 ^{e-q} ±0.1	1.57 ^{a-g} ±0.2	1.21 ^{1-q} ±0.1	1.19 ^{h-q} ±0.1	1.06 ^q ±0.1	1.29 ^{e-q} ±0.1	1.26 ^c
Mean	1.36 ^a	1.40 ^a	1.36 ^a	1.36 ^a	1.47 ^a	1.34 ^a	1.43 ^a	1.41 ^a	1.46 ^a	1.42 ^a	1.40 ^a	1.36 ^a	1.48 ^a	
Chlorophyll b														
Control ₂	0.529 ^{c-s} ±0.2	0.491 ^{1-s} ±0.1	0.561 ^{c-s} ±0.1	0.759 ^{ab} ±0.1	0.432 ^{r-1} ±0.1	0.483 ^{u-s} ±0.1	0.645 ^{a-k} ±0.1	0.512 ^{1-s} ±0.1	0.488 ^{m-s} ±0.1	0.601 ^{d-p} ±0.1	0.599 ^{c-q} ±0.2	0.534 ^{d-s} ±0.1	0.619 ^{b-n} ±0.125	0.55 ^b
CS+Z	0.538 ^{c-q} ±0.1	0.538 ^{c-s} ±0.1	0.430 ^{c-1} ±0.2	0.277 ^u ±0.1	0.571 ^{c-s} ±0.1	0.302 ^{1b} ±0.1	0.698 ^{a-c} ±0.2	0.583 ^{c-q} ±0.1	0.614 ^{b-q} ±0.1	0.581 ^{c-q} ±0.2	0.555 ^{c-s} ±0.1	0.545 ^{d-s} ±0.2	0.673 ^{a-g} ±0.1	0.53 ^{bc}
CS+T	0.523 ^{b-s} ±0.1	0.423 ^{z-u} ±0.3	0.427 st ±0.3	0.451 ^{u-s} ±0.2	0.514 ^{d-1} ±0.1	0.610 ^{c-o} ±0.2	0.689 ^{a-d} ±0.1	0.577 ^{r-1} ±0.1	0.597 ^{c-q} ±0.2	0.594 ^{d-q} ±0.3	0.518 ^{c-s} ±0.3	0.683 ^{a-e} ±0.3	0.654 ^{a-1} ±0.2	0.55 ^b
CS+CC	0.617 ^{b-o} ±0.1	0.691 ^{a-d} ±0.4	0.658 ⁸⁻¹ ±0.2	0.637 ^{b-1} ±0.1	0.557 ^{r-s} ±0.0	0.536 ^{c-s} ±0.3	0.526 ^{8-s} ±0.1	0.670 ^{a-b} ±0.2	0.696 ^{a-c} ±0.3	0.587 ^{a-q} ±0.2	0.787 ^m ±0.1	0.675 ^{a-f} ±0.3	0.664 ^{a-1} ±0.1	0.63 ^a
CC+B	0.536 ^{c-s} ±0.1	0.452 ^{q-s} ±0.1	0.523 ^{b-s} ±0.1	0.521 ^{1-s} ±0.1	0.505 ^{k-s} ±0.0	0.522 ^{2-1b} ±0.1	0.605 ^{c-1b} ±0.2	0.478 ^{m-s} ±0.1	0.514 ^{d-1} ±0.1	0.470 ^{a-s} ±0.1	0.460 ^{p-s} ±0.1	0.533 ^{3-1b} ±0.1	0.487 ^{m-s} ±0.1	0.50 ^c
Mean	0.548 ^{c-e}	0.538 ^{c-e}	0.520 ^{de}	0.529 ^{c-e}	0.516 ^{de}	0.491 ^e	0.633 ^a	0.587 ^{m-c}	0.581 ^{a-d}	0.566 ^{1-d}	0.560 ^{b-d}	0.594 ^{a-c}	0.619 ^{ab}	

(Continues)

TABLE 7 | (Continued)

Filler	Binder													Mean
	Control ₁	GA ₁	GA ₂	GA ₃	GA ₄	SD ₁	SD ₂	SD ₃	SD ₄	CMC ₁	CMC ₂	CMC ₃	CMC ₄	
Carotenoid														
Control ₂	1.183 ^{a-c} ± 0.02	1.189 ^{a-c} ± 0.2	1.372 ^{b-c} ± 0.3	1.464 ^{d-m} ± 0.1	1.344 ^{d-e} ± 0.1	1.289 ^d ± 0.2	1.089 ^d ± 0.02	1.296 ^d ± 0.2	1.290 ^d ± 0.1	1.161 ^d ± 0.1	1.163 ^d ± 0.1	1.352 ^{b-a} ± 0.1	1.451 ^{d-m} ± 0.2	1.28 ^d
CS+Z	1.509 ^{b-k} ± 0.3	1.491 ^{c-l} ± 0.2	1.408 ^{e-g} ± 0.3	0.704 ^u ± 0.1	1.386 ^{e-f} ± 0.1	1.327 ^e ± 0.2	1.741 ^{ab} ± 0.1	1.520 ^{b-j} ± 0.3	1.596 ^{b-b} ± 0.1	1.458 ^{d-m} ± 0.1	1.458 ^{d-m} ± 0.1	1.364 ^{b-a} ± 0.1	1.734 ^{a-c} ± 0.1	1.43 ^b
CS+T	1.122 ^a ± 0.03	1.122 ^a ± 0.0	1.174 ^p ± 0.1	1.398 ^f ± 0.1	1.563 ^{b-c} ± 0.2	1.372 ^{e-f} ± 0.2	1.432 ^{e-a} ± 0.2	1.546 ^{b-l} ± 0.2	1.612 ^{a-g} ± 0.2	1.237 ^{m-l} ± 0.1	1.236 ^{m-l} ± 0.1	1.597 ^{b-b} ± 0.1	1.422 ^{e-o} ± 0.1	1.37 ^{bc}
CS+CC	1.475 ^{d-m} ± 0.01	1.647 ^{a-c} ± 0.0	1.643 ^{a-f} ± 0.2	1.412 ^{e-p} ± 0.1	1.544 ^{b-c} ± 0.3	1.404 ^{e-a} ± 0.2	1.499 ^{b-l} ± 0.1	1.507 ^{b-k} ± 0.1	1.502 ^{b-l} ± 0.1	1.264 ^{k-l} ± 0.2	1.854 ^d ± 0.2	1.467 ^{d-m} ± 0.1	1.696 ^{a-d} ± 0.2	1.53 ^a
CC+B	1.352 ^{b-a} ± 0.1	1.259 ^d ± 0.1	1.414 ^{e-p} ± 0.1	1.259 ^d ± 0.1	1.341 ^{i-s} ± 0.1	1.280 ^{l-t} ± 0.2	1.376 ^{e-f} ± 0.3	1.374 ^{e-f} ± 0.2	1.457 ^{d-m} ± 0.1	1.152 ^{v-l} ± 0.1	1.192 ^{m-l} ± 0.3	1.386 ^{e-f} ± 0.3	1.483 ^{d-m} ± 0.2	1.33 ^{cd}
Mean	1.32 ^{d-f}	1.34 ^{c-f}	1.40 ^{b-e}	1.25 ^f	1.43 ^{b-d}	1.33 ^{d-f}	1.49 ^{ab}	1.44 ^{a-c}	1.49 ^{ab}	1.25 ^f	1.31 ^{ef}	1.43 ^{b-d}	1.55 ^a	

Note: Data represented from four replications. Means followed by the same letter in each treatment were not different by Duncan's multiple range test ($p \leq 0.05$), binder material: control₁ (seed free of binder), GA₁ = 20 g gum arabic per 10 g seed⁻¹, GA₂ = 30 g gum arabic per 10 g seed⁻¹, GA₃ = 40 g gum arabic per 10 g seed⁻¹, GA₄ = 50 g gum arabic per 10 g seed⁻¹, SD₁ = 20 g selenium dioxide per 10 g seed⁻¹, SD₂ = 30 g selenium dioxide per 10 g seed⁻¹, SD₃ = 40 g selenium dioxide per 10 g seed⁻¹, SD₄ = 50 g selenium dioxide per 10 g seed⁻¹, CMC₁ = 20 g carboxymethylcellulose per 10 g seed⁻¹, CMC₂ = 30 g carboxymethylcellulose per 10 g seed⁻¹, CMC₃ = 40 g carboxymethylcellulose per 10 g seed⁻¹, CMC₄ = 50 g carboxymethylcellulose per 10 g seed⁻¹, filler material: control₂ (seed free of filler), CS+Z = 30 g calcium sulphate + 100 g talc per 10 g seed⁻¹, CS+T = 30 g calcium sulphate + 100 g talc per 10 g seed⁻¹, CS+CC = 200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹, CC+B = 200 g calcium carbonate + 50 g bentonite per 10 g seed⁻¹.

3.1.9.3 | Dissolution Time. The average values of dissolution time for pelleted seeds were 6–1200 s. In all treatments (filler), the dissolution time of plated seeds increased with increasing binder content. The dissolution time was the desired characteristic of pelleted seeds (Table 8). The dissolution time for pelleted seeds varies depending on the materials used for pelleting and the size of the pellets. Generally, larger pellets tend to have longer dissolution times in water, and they delay seed germination (Asagi et al. 2008).

3.1.9.4 | Pelletisation Efficiency (PE). The average fragmentation number for pelleted seeds was 81%–95%. The highest values of pelletisation efficiency were observed in seeds pelleted with a combination of CS+CC (200 g calcium sulphate + 50 g calcium carbonate per 10 g seed⁻¹), and CMC₂ (30 g carboxymethylcellulose per 10 g seed⁻¹) (Table 8). During the seed pelleting process, some pellets are not uncommon to form without seeds, often called ‘empty pellets’ or ‘seedless pellets’. These are essentially clumps of filler compounds and binding agents that adhere together without encapsulating a seed. Empty pellets can cause issues during mechanical sowing and decrease the uniform distribution of actual seeds.

3.2 | Experiment 2: Antifungal Effect of Plant Extracts on the Fungal Colony (FC) Size and Percent Inhibition (PI) of *R. solani*: An In Vitro Study

Laboratory experiments allowed us to observe the direct effect of plant extracts on the growth dynamics of *R. solani* (Figure 5).

The largest FC size (1.33 mm) was observed in the culture medium containing 500 ppm of *S. rosmarinus* extract, while the smallest FC size (0.36 mm) was found in the medium with 2000 ppm of *T. vulgaris* extract (Table 10). The interaction between the type and concentration of the plant extract had a significant effect on the percent inhibition (PI) of *R. solani* growth (Table 9). Increasing concentration of the plant extracts in the culture medium led to a decrease in the PI (Table 10). The highest PI (1.33 mm) was observed in the culture medium containing 2000 ppm of *T. vulgaris* extract, while its lowest value (0.36 mm) was found in the medium with 500 ppm of *S. rosmarinus* extract (Table 10). The results indicated that *T. vulgaris* extract was more effective in inhibiting the growth of *R. solani* compared to the other plant extracts across all concentrations (Table 10). Finally, the treatment containing 2000 ppm of *T. vulgaris* extract was the most suitable treatment for controlling *R. solani*. Traditionally, seed fungicide treatments have been used to reduce damping-off damage. However, with the increased focus on reducing environmental pollution, the use of natural fungicides has been recommended. Some of the plant-based compounds may have potential as natural fungicides. Studies have shown that essential oils from plants like *T. vulgaris* (thyme) can have antifungal activity against *R. solani*, the primary causal agent of damping-off, which is consistent with the findings of (Chauhan et al. 2017). The minimum inhibitory concentration (MIC) of thyme oil is considerably lower than that of some synthetic fungicides, indicating its potential as a natural alternative for managing this fungal pathogen (Khaledi et al. 2015). The primary active compounds in *T. vulgaris*, the essential oil of thyme, include thymol and carvacrol, both of which exhibit strong antifungal properties. These compounds disrupt

TABLE 8 | Effect of filler and binder on sphericity (%), fragmentation (no.), dissolution time (s) and pelletisation efficiency (%) of canola pelleted seeds.

Filler	Binder												Mean
	GA ₁	GA ₂	GA ₃	GA ₄	SD ₁	SD ₂	SD ₃	SD ₄	CMC ₁	CMC ₂	CMC ₃	CMC ₄	
Sphericity (%)													
CS + CC	0.963	0.976	0.982	0.996	0.932	0.952	0.984	0.992	0.980	0.963	0.98	0.999	0.974
CS + Z	0.971	0.969	0.999	0.984	0.958	0.971	0.982	0.991	0.918	0.945	0.986	0.999	0.972
CS + T	0.98	0.998	0.983	0.95	0.941	0.956	0.982	0.999	0.966	0.971	0.982	0.999	0.975
CC + B	0.962	0.987	0.984	0.999	0.932	0.965	0.974	0.991	0.919	0.968	0.975	0.991	0.970
Mean	0.969	0.982	0.987	0.982	0.940	0.961	0.980	0.993	0.945	0.961	0.980	0.997	
Fragmentation (per/50 seeds)													
CS + CC	20	18	16	10	18	16	14	13	16	14	12	10	14.750
CS + Z	19	17	15	9	16	14	12	11	15	13	11	9	13.416
CS + T	18	16	14	8	16	14	12	11	12	10	8	6	12.083
CC + B	19	17	15	9	17	15	13	12	13	11	9	7	13.083
Mean	19	17	15	9	16.75	14.75	12.75	11.75	14	12	10	8	
Dissolution time(s)													
CS + CC	20	30	420	720	21	50	180	300	60	121	600	1200	310.16
CS + Z	22	58	70	120	58	63	116	151	60	87	95	111	84.25
CS + T	9	15	48	56	6	10	20	21	12	21	30	45	24.416
CC + B	50	58	60	68	20	25	30	50	25	30	44	60	43.333
Mean	25.25	40.25	149.5	241	26.25	37	86.5	130.5	39.25	64.75	192.2	354	
Pelletisation efficiency (%)													
CS + CC	85	86	88	87	90	90	90	90	90	95	90	90	88.83
CS + Z	83	84	86	85	90	91	93	92	91	90	93	90	89
CS + T	80	81	83	82	90	90	90	90	90	92	90	93	87.58
CC + B	85	86	88	87	95	97	98	90	90	94	94	95	91.5
Mean	83.25	84.25	86.25	85.25	91.25	92	92.75	90.5	90.25	91.25	91.75	92	

Note: Binder material: GA₁ = 20g gum arabic per 10g seed⁻¹, GA₂ = 30g gum arabic per 10g seed⁻¹, GA₃ = 40g gum arabic per 10g seed⁻¹, GA₄ = 50g gum arabic per 10g seed⁻¹, SD₁ = 20g selenium dioxide per 10g seed⁻¹, SD₂ = 30g selenium dioxide per 10g seed⁻¹, SD₃ = 40g selenium dioxide per 10g seed⁻¹, SD₄ = 50g selenium dioxide per 10g seed⁻¹, CMC₁ = 20g carboxymethylcellulose per 10g seed⁻¹, CMC₂ = 30g carboxymethylcellulose per 10g seed⁻¹, CMC₃ = 40g carboxymethylcellulose per 10g seed⁻¹, CMC₄ = 50g carboxymethylcellulose per 10g seed⁻¹, filler material: CS+Z = 30g calcium sulphate + 100g zeolite per 10g seed⁻¹, CS+T = 30g calcium sulphate + 100g talc per 10g seed⁻¹, CS+CC = 200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹, CC+B = 200g calcium carbonate + 50g bentonite per 10g seed⁻¹.

fungal cell membranes and generate reactive oxygen species (ROS), leading to cell death in the pathogen (Kim et al. 2019). The active compounds in the medicine plant extract may disrupt the fungal cell wall or interfere with their metabolic processes, although the specific mechanisms require further investigation (Khaledi et al. 2015).

3.3 | Experiment 3: Effects of Binder, Filler and Plant Extract Treatments on Emergence Quality and Early Growth of Canola in Soil Infected With *R. solani*: A Greenhouse Study

The analysis of variance (ANOVA) indicated that the treatments (extract and concentrations of *T. vulgaris*, *L. officinalis*, *C. verum*

and *S. rosmarinus*) had a significant effect on the emergence percentage, emergence rate, leaf number, root value, root dry weight, shoot dry weight and plant weight vigour index of the canola seedlings (Table 11).

The emergence percentage, emergence rate, leaf number, root value, root dry weight, shoot dry weight and plant weight vigour index increased with increasing extract concentration. This effect was observed in all treatments, but its slope was higher in the *T. vulgaris* extract treatment (Table 12). The lowest emergence percentage, emergence rate and seedling characteristics were observed in the seed pelleted with free extract. The emergence percentage, emergence rate, leaf number, shoot dry weight, root dry weight and seedling weight vigour index increased with increasing concentration of the plant extract (Table 12). The results

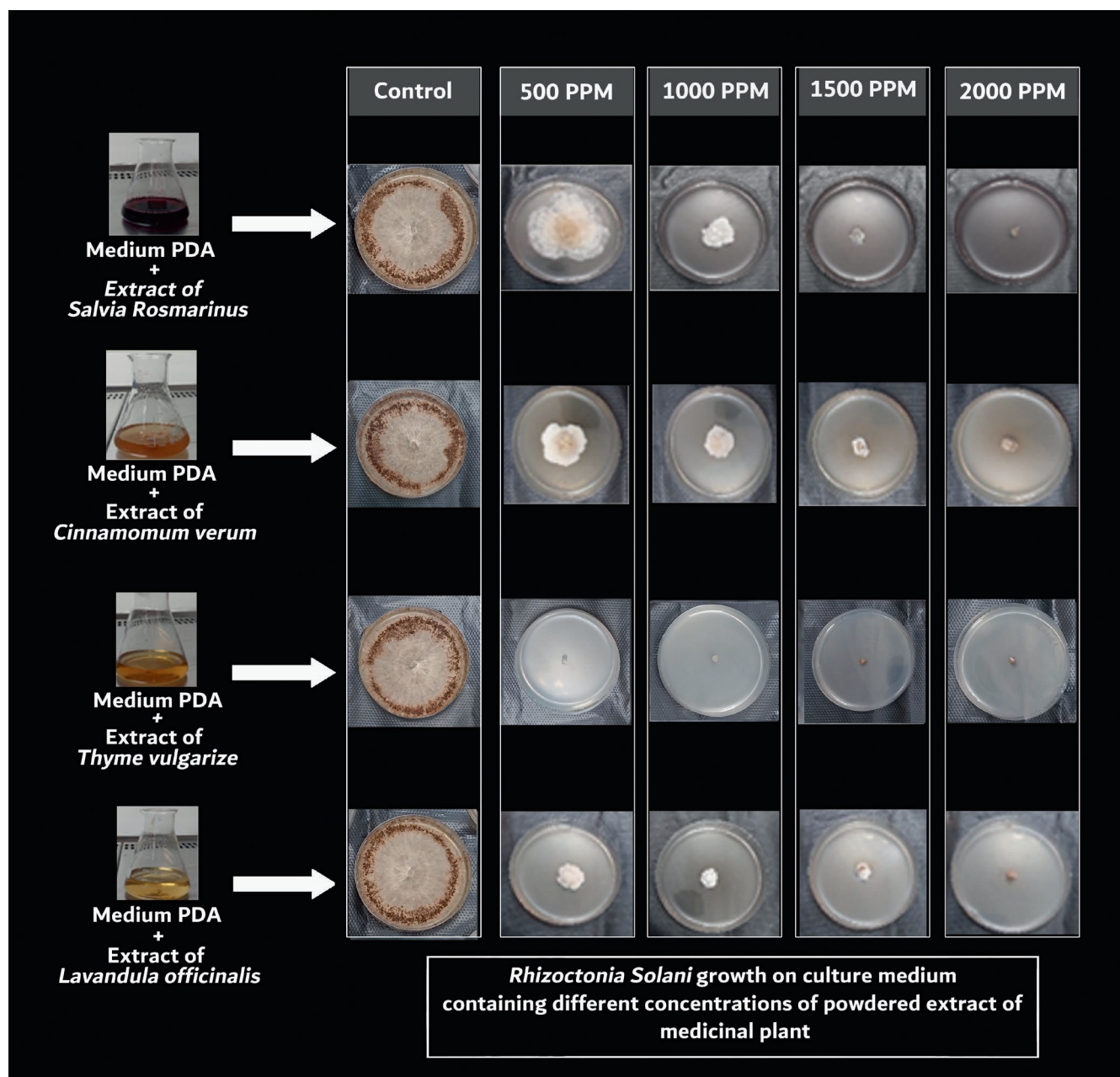


FIGURE 5 | The figure shows the second experiment protocol followed by PDA (potato dextrose agar). The severity of *Rhizoctonia solani*, the fungal colony (FC) size, was significantly affected by the interaction between the type and concentration of plant extracts (Table 9). The highest FC size of *R. solani* was observed in the control treatment (PDA medium without any antifungal plant extract). However, the addition of the plant extracts to the culture medium reduced the FC size. The FC size of *R. solani* decreased with increasing concentration of the plant extract.

indicated that the emergence percentage, emergence rate and seedling characteristics were influenced by the type of extract (Table 11). The highest emergence percentage, emergence rate and seedling characteristics were observed in the seed pelleted with *T. vulgaris* extract (Table 12). The interaction between the type and concentration of the plant extract had a significant effect on the emergence percentage, emergence rate and seedling characteristics (Table 11). The highest emergence percentage (67%), emergence rate (0.085 seed day⁻¹), leaf number (9.6), shoot dry weight (0.42g), root dry weight (0.35g) and seedling weight vigour index (57.49) were observed in the seeds pelleted with 2000ppm of *T. vulgaris* extract (Table 12). The extract of *T. vulgaris* at a concentration of 2000ppm was found to be the most effective treatment for

controlling *R. solani* disease in canola seedlings. Other researchers have reported that essential oils derived from thyme, clove and oregano can effectively control *R. solani* in broccoli seedlings when applied as a 5% aqueous emulsion (i.e., 5 mL per 150 mL of soil) before planting. This greenhouse treatment significantly reduced the incidence of rot symptoms. Coating faba bean seeds with thyme extract reduced root rot disease by 50%, whereas the chemical fungicide Rizolex-T reduced it by only 16.1%. An even better additive effect was achieved with a combination treatment involving the fungus *Trichoderma harzianum*. Other researchers have reported that Thymus species are a rich source of phenolic terpenoids and carvacrol. Carvacrol disrupts the plasma membrane of pathogens, leading to the leakage of ATP and potassium ions and ultimately

cell death (Pank et al. 2004; Juven et al. 1994). Therefore, the antioxidant and antimicrobial activities of thyme extract can be attributed to these compounds.

TABLE 9 | Effect of antifungal effect on the plant (*Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus*) extracts on fungal colonies.

Mean square			
Source	df	FC	PI
E	3	1.4018867**	154.47787**
C	4	220.6190233**	18232.97713**
E*C	12	0.8696300**	23.95675**
Error	40	0.2618000	2.16364
CV%		4.81	2.11

Abbreviations: C = concentration, E = extract, FC = fungal colonies, PI = percent inhibition.
** and *Significant at the 1%, significant at the 5% probability level, and not significant.

TABLE 10 | Analysis of variance of fungal colony size and percent inhibition as affected by the antifungal effect of the plant (*Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus*) extracts.

Bio extract	Concentration				
	0 (ppm)	500 (ppm)	1000 (ppm)	1500 (ppm)	2000 (ppm)
FC					
E ₁	5.5 ^a ± 0	0.76 ^{ef} ± 0.05	0.63 ^{f-h} ± 0.06	0.56 ^{g-j} ± 0.02	0.49 ^{i-k} ± 0.04
E ₂	5.5 ^a ± 0	0.57 ^{ghij} ± 0.05	0.50 ^{h-j} ± 0.04	0.45 ^{jk} ± 0.02	0.36 ^{ik} ± 0.06
E ₃	5.5 ^a ± 0	1.35 ^b ± 0.13	0.92 ^{cd} ± 0.08	0.64 ^{fg} ± 0.05	0.54 ^{g-j} ± 0.07
E ₄	5.5 ^a ± 0	1.3 ^b ± 0.17	1.03 ^c ± 0.15	0.86 ^{de} ± 0.14	0.6 ^{g-i} ± 0.10
PI					
E ₁	0 ^k ± 0	86.24 ^{fg} ± 0.93	88.48 ^{d-f} ± 1.04	89.76 ^{b-e} ± 0.38	91.03 ^{a-c} ± 0.74
E ₂	0 ^k ± 0	89.64 ^{c-e} ± 0.83	90.85 ^{b-d} ± 0.75	91.78 ^{ab} ± 0.42	93.45 ^a ± 1.1
E ₃	0 ^k ± 0	75.45 ^j ± 2.4	83.33 ^{hi} ± 1.32	88.24 ^{ef} ± 0.2	90.18 ^{b-e} ± 1.26
E ₄	0 ^k ± 0	76.36 ^j ± 3.14	81.2 ^{li} ± 2.77	84.36 ^{gh} ± 2.62	89.09 ^{c-e} ± 1.82

Note: Means with the same letter are not significantly different.
Abbreviations: E1 = *Lavandula officinalis* extract, E2 = *Thymus vulgaris* extract, E3 = *Salvia rosmarinus* extract, E4 = *Cinnamomum verum* extract, FC = fungal colonies, PI = percent inhibition.

TABLE 11 | Analysis of variance, emergence percentage and seedling characteristics as affected by the antifungal effect of extract and concentrations of *Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus*.

Source	df	EP	ER (seed day ⁻¹)	LN	RV	RDW (g)	SDW (g)	PWVI
E	3	6218.33**	0.0005ns	4.979**	0.814**	0.009**	0.096**	6491.71**
C	4	1607.50**	0.0004ns	9.781**	5.09**	0.367**	0.128**	5258.18**
A*B	12	526.66**	0.0004ns	2.447**	0.097**	0.003**	0.011**	761.74**
Error	60	82.50	0.0001	0.220	0.008	0.0005	0.0003	38.01
CV%		22.28	13.36	5.18	4.8	6.72	5.59	20.17

Abbreviations: EP = emergence percentage, ER = emergence rate, LN = leaf number, PWVI = plant weight vigour index, RDW = root dry weight, RV = root value, SDW = shoot dry weight.
** and *Significant at the 1%, significant at the 5% probability level, and not significant.

4 | Conclusion

The results demonstrated that canola seeds pelleted with a combination of CS + CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹) showed the highest emergence rate (ER) and improved growth traits, such as leaf area (LA), number of leaves (NL), shoot length (SL), root length (RL), plant length (PL), plant length vigour index (PLVI), shoot growth rate (SGR), SPAD index, carotenoid content, chlorophyll *a* content, chlorophyll *b* content, leaf relative water content (RWC), root value, leaf dry weight, shoot dry weight, root dry weight (RDW), plant dry weight and plant weight vigour index (PWVI). The use of CMC₂ as a binder in seed pelleting, along with calcium sulphate (CS) and calcium carbonate (CC), helped in easy pellet formation and provided uniform coating on the seeds. Because the seeds pelleted with this combination had the highest sphericity, pelleting efficiency (PE), and a balanced state of fragmentation number and dissolution time. Based on these findings, it is recommended to use the seed pelleting combination CS + CC (200g calcium sulphate + 50g calcium carbonate per 10g seed⁻¹), and CMC₂ (30g carboxymethylcellulose per 10g seed⁻¹) to achieve

TABLE 12 | Effect of antifungal effect of extract and concentrations of *Thymus vulgaris*, *Lavandula officinalis*, *Cinnamomum verum* and *Salvia rosmarinus* on emergence percentage and seedling characteristics.

	Concentration					
Plant	Control	L500	L1000	L1500	L2000	Mean
<i>Emergence percentage</i>						
Lavandula	20 ^h ± 11.54	22 ^h ± 0	27g ^h f ^g ± 0	35 ^f g ± 15	37.5 ^e - ^g ± 9.57	30 ^b
Thymus	20 ^h ± 11.54	62.5 ^{cd} ± 5	70 ^{bc} ± 0	80 ^{ab} ± 0	92.5 ^a ± 5	67 ^a
Rosmarinus	20 ^h ± 11.54	22 ^h ± 0	25 ^h ± 0	35 ^f g ± 5.77	50 ^{de} ± 0	31 ^b
Cinnamomum	20 ^h ± 11.54	27 ^{gh} ± 12.5	30 ^{gh} ± 11.54	32.5 ^f - ^g ± 12.58	45 ^{ef} ± 17.32	35 ^b
Mean	30 ^d	35 ^{cd}	38.75 ^{bc}	43.75 ^b	56.25 ^a	
<i>Emergence rate</i>						
Lavandula	0.0100 ^{a-c} ± 0	0.0870 ^{b-e} ± 0.02	0.01144 ^a ± 0.004	0.08 ^{c-e} ± 0.03	0.1065 ^a ± 0.004	0.021 ^{ab}
Thymus	0.0100 ^{a-c} ± 0	0.093 ^{a-d} ± 0.001	0.1051 ^a ± 0.008	0.10 ^{a-c} ± 0.002	0.109 ^a ± 0.003	0.085 ^a
Rosmarinus	0.0100 ^{a-c} ± 0	0.0780 ^{de} ± 0.01	0.0736 ^e ± 0.03	0.09 ^{a-c} ± 0.01	0.099 ^{a-c} ± 0.006	0.071 ^b
Cinnamomum	0.0100 ^{a-c} ± 0	0.063 ^{a-d} ± 0.005	0.0870 ^{c-e} ± 0.01	0.088 ^{c-g} ± 0.001	0.098 ^{a-c} ± 0.002	0.069 ^c
Mean	0.100 ^{ab}	0.091 ^b	0.096 ^{ab}	0.101 ^a	0.105 ^a	
<i>Number of leaves</i>						
Lavandula	7.25 ^f ± 0.5	8.5 ^{ed} ± 0.5	9.5 ^{bc} ± 0.5	9.75 ^b ± 0.5	9.5 ^{bc} ± 0.5	9.2 ^c
Thymus	9.75 ^b ± 0.5	8 ^e ± 0	8.75 ^d ± 0	9 ^{cd} ± 0	12.25 ^a ± 0.5	9.6 ^a
Rosmarinus	9.75 ^b ± 0.5	9 ^{cd} ± 0	9 ^{cd} ± 0	8 ^e ± 0.8	9.5 ^{bc} ± 1	9.05 ^b
Cinnamomum	9.75 ^b ± 0.5	9 ^{cd} ± 0.5	8 ^e ± 0	8 ^e ± 0	9 ^{cd} ± 0	8.4 ^b
Mean	9.75 ^a	8.43 ^b	8.62 ^b	8.43 ^b	10.06 ^a	
<i>Root value</i>						
Lavandula	1.3 ^k ± 0.08	1.6 ^{fg} ± 0.2	2.20 ± 0.19	2.3 ^{cd} ± 0	2.82 ^b ± 0.05	2.05 ^a
Thymus	1.3 ^k ± 0.08	1.72 ^{hi} ± 0.1	2.22 ^f ± 0.05	2.4 ^d ± 0.08	3.17 ^a ± 0.02	2.16 ^a
Rosmarinus	1.3 ^k ± 0.08	1.43 ^j ± 0.02	1.8 ^{gh} ± 0	2.2 ^e ± 0.04	2.61 ^c ± 0.08	1.86 ^b
Cinnamomum	1.3 ^k ± 0.08	1.43 ^j ± 0.1	1.65 ⁱ ± 0.04	1.87 ^g ± 0.06	2.43 ^d ± 0.06	1.73 ^c
Mean	1.3 ^e	1.62 ^d	1.93 ^c	2.24 ^b	2.76 ^a	
<i>Root dry weight</i>						
Lavandula	0.150 ^j ± 0.32	0.237 ⁱ ± 0.03	0.353 ^{ef} ± 0.01	0.417 ^d ± 0.01	0.505 ^b ± 0.01	0.324 ^b
Thymus	0.150 ^j ± 0.32	0.271 ^h ± 0.01	0.380 ^e ± 0.2	0.445 ^d ± 0.03	0.550 ^a ± 0.008	0.359 ^a
Rosmarinus	0.150 ^j ± 0.32	0.150 ^j ± 0.32	0.373 ^{ef} ± 0.004	0.434 ^d ± 0.02	0.481 ^c ± 0.01	0.306 ^c
Cinnamomum	0.150 ^j ± 0.32	0.121 ^j ± 0.024	0.330 ^g ± 0.01	0.426 ^d ± 0.009	0.528 ^{ab} ± 0.01	0.33 ^b
Mean	0.150 ^e	0.215 ^d	0.357 ^c	0.430 ^b	0.519 ^a	
<i>Shoot dry weight</i>						
Lavandula	0.281 ⁱ ± 0.01	0.217 ^k ± 0.012	0.273 ^{ij} ± 0.01	0.285 ⁱ ± 0	0.377 ^e ± 0.02	0.286 ^c
Thymus	0.281 ⁱ ± 0.01	0.325 ^{gh} ± 0.02	0.375 ^e ± 0.01	0.466 ^c ± 0.04	0.652 ^a ± 0.03	0.420 ^a
Rosmarinus	0.281 ⁱ ± 0.01	0.266 ^{ij} ± 0.007	0.369 ^{ef} ± 0.02	0.428 ^d ± 0.02	0.539 ^b ± 0.01	0.377 ^b
Cinnamomum	0.281 ⁱ ± 0.01	0.199 ^k ± 0.027	0.250 ^j ± 0	0.312 ^h ± 0	0.345 ^{fg} ± 0.01	0.277 ^c
Mean	0.252 ^e	0.281 ^d	0.317 ^c	0.373 ^b	0.478 ^a	

(Continues)

TABLE 12 | (Continued)

	Concentration					
Plant	Control	L500	L1000	L1500	L2000	Mean
<i>Plant Weight Vgor Index</i>						
Lavandula	8.6 ^k ± 5.82	9.1 ^{jk} ± 0.78	19.90 ^{f-h} ± 4.53	24.57 ^{g-i} ± 10.89	33.07 ^{de} ± 8.84	19.59 ^b
Thymus	8.6 ^{i-k} ± 5.82	37.25 ^{de} ± 2.94	52.89 ^c ± 2.54	72.91 ^b ± 5.43	111.2 ^a ± 5.35	57.49 ^a
Rosmarinus	8.6 ^{i-k} ± 5.82	9.75 ^k ± 0.48	18.3 ^{h-k} ± 0.36	30.17 ^{ef} ± 4.13	51.06 ^c ± 0.99	23.27 ^b
Cinnamomum	8.6 ^k ± 5.82	8.46 ^{g-k} ± 4.88	17.48 ^{g-j} ± 6.73	23.89 ^{fg} ± 6.6	39.28 ^d ± 14.2	21.89 ^b
Mean	8.6 ^d	16.26 ^d	26.42 ^c	37 ^b	58.6 ^a	

Note: Data represented from four replications. Means followed by the same letter in each trait were not different by Duncan's multiple range test ($p \leq 0.05$).

Abbreviations: EP = emergence percentage, ER = emergence rate, NL = number of leaves, PWVI = plant weight vigour index, RDW = root dry weight, RV = root value, SDW = shoot dry weight.

uniform and synchronised seedling germination and early growth in canola. Furthermore, the essential oils from *T. vulgaris* (thyme) have demonstrated strong fumigant antifungal activity against *R. solani*, the phytopathogenic fungus. *Thymus vulgaris* extract can be used as a practical and potentially environmentally friendly antifungal agent in the seed pelleting process for managing *R. solani*.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** jph70203-sup-0001-AppendixS1.docx.