



Article

A Different Way to Sow: Seed Enhancements Involving Gelatin Encapsulation with Controlled-Released Fertilizers Improve Seedling Growth in Tomato (*Solanum lycopersicum* L.)

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Abstract: Seed enhancements involve post-harvest modifications that improve germination and plant performance. One form of enhancement involves coatings, which encompasses encrusting, pelleting, and film coats. These coatings may contain agrichemicals, such as fungicides and insecticides, and can foster conformational changes that improve the plantability of small or irregularly shaped seeds. Seed encapsulation using pharmaceutical capsules can be viewed as an extension of seed coatings where seeds and other beneficial agrichemicals can be combined into a single plantable unit. For many crops, direct contact with high levels of conventional fertilizers may induce some level of phytotoxicity, and early studies involving fertilizer-enriched seed coatings resulted in decreased seedling emergence and diminished plant performance. Encapsulation, however, provides greater delivery volumes compared to other coatings and may offer some degree of separation between seeds and potentially phytotoxic agrichemicals. This study considered tomato seed encapsulation with controlled-release fertilizers. In general, seed exposure to gelatin-based capsules delayed germination by 2- to 3- days. Nevertheless, seed encapsulation improved plant performance including increased plant height and dry mass production by as much as 75 and 460%, respectively. These growth responses mitigated any effects attributed to germination delays. Moreover, higher levels of controlled-release fertilizers (≥ 800 mg) fostered earlier flower induction by up to 3 weeks. Collectively, the results suggest that seed encapsulation can be an effective way to deliver fertilizers to plants in a manner that could reduce overall fertilizer application rates and possibly lessen the quantity of plant nutrient input necessary for tomato cultivation.

Keywords: capsule; fertilizer; gelatin; plant growth; seed encapsulation; seed enhancement



Academic Editor: Shan-Li Wang

Received: 17 December 2024

Revised: 9 February 2025

Accepted: 12 February 2025

Published: 20 February 2025

Citation: Touchette, B.W.; Cox, D.S.; Carranza, R.L.; Palms, H. A Different Way to Sow: Seed Enhancements Involving Gelatin Encapsulation with Controlled-Released Fertilizers Improve Seedling Growth in Tomato (*Solanum lycopersicum* L.). *Agrochemicals* 2025, 4, 2. <https://doi.org/10.3390/agrochemicals4010002>

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1. Introduction

Seed enhancements involve post-harvest modifications that improve germination, plant performance, and/or seed handling and plantability [1,2]. In general, seed enhancements are classified into three techniques including coating, conditioning, and liquid priming [1,3]. These techniques may be combined to provide cumulative benefits that improve seed quality and enhance overall plant performance.

Seed coatings, specifically, may include pelleting, encrusting, or film coats. Pelleting involves the layering of materials that alter the size and shape of the original seed, resulting in conformational changes that improve plantability of small or irregularly shaped

seeds [4,5]. To provide additional benefits to the emerging seedlings, pelleted materials may also contain agrichemicals such as fungicides and insecticides [6,7]. Film coatings, which typically weigh less than 10 percent of the total seed mass, involve the uniform deposition of colorants, plasticizers, and/or polymers forming a protective film around the seed [1,8]. The improved uniformity of film-coated seeds may also enhance flow characteristics in mechanical planters [4,9] and like pelleting, agrichemicals, plant protectants, and beneficial microbes can be applied to the seed [10,11]. Spatial separations between the seed surface and agrichemicals in film coatings, however, are not as great as those achieved through pelleting or encrusting, and depending on the nature of the applied chemical(s), film-coatings can be more inhibitory or toxic to seeds of some crops [1,9].

For many plants, direct contact with high levels of conventional fertilizers induces some level of phytotoxicity. While phosphorus is among the least harmful elements for germinating seedlings, elevated levels of soil phosphorus can negatively impact plant performance [10], and lower sublethal-concentrations may delay or diminish seed germination [12]. More typically, free ammonia is the primary toxic agent found in fertilizers [10,13] and, during germination, can prevent seedling development through seminal root injury and root apex necrosis [13]. In urea-enhanced seed coatings, Scott et al. [14] observed decreased seedling emergence in wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.). Other researchers have observed poor plant performance due to nutrient coatings in wet soils [15] or in coarse-texture soils [16]. Collectively, it is thought that the adverse plant responses to fertilizer enriched seed coatings, attributed to the proximal placement of plant nutrients, may depend on soil properties such as temperature, moisture, pH, texture, and sorption capacity, as well as the volume of growth media in which the fertilizer is ultimately placed [10]. Interestingly, early studies on seed coatings found that less soluble fertilizers tended to be less damaging to seeds [17]; however, under these conditions, efficacy was also diminished [10]. Notwithstanding, controlled-released (coated) fertilizers may lead to greater nutrient efficiency, and when placed near seeds, appear to produce less damage to plants than conventional uncoated fertilizers [10,18,19].

A possible extension of seed coatings is the use of pharmaceutical capsules in which seeds and other beneficial agrichemicals can be combined into a single plantable unit [20,21]. In doing so, seed encapsulation may provide the benefits of both pelleting and film coating, as seed encapsulation offers uniformity with reduced friction for mechanical planters, provides a level of separation between chemicals and seeds (potentially reducing phytotoxicity), and limits the exposure of workers to potentially harmful agrichemicals. Moreover, encapsulating controlled-release fertilizers with seeds may improve nutrient efficiency and lessen fertilizer injury, thereby providing a competitive advantage—or ‘starter effect’—during early plant establishment [10,13]. Unfortunately, little is known about the potential benefits of encapsulating controlled-released fertilizers with seeds and how this technique may influence overall plant emergence as well as early growth and development. Therefore, the purpose of this study was to consider germination and early growth of tomatoes (*Solanum lycopersicum* L.) that were grown from seeds encapsulated in gelatin with up to 1600 mg of controlled-released fertilizers.

2. Materials and Methods

2.1. Experiment 1—Seed Germination and Vigor

Germination and vigor of tomato seeds (*Solanum lycopersicum* L. cv. Red Cherry; syn. *Lycopersicon esculentum* Mill.) were analyzed according to Demir et al. [22]. Approximately twenty seeds were placed between moisten paper towels in a 90 mm diameter petri dish. Five mL of distilled water (control; n = 4) or type-A gelatin solution (0.10, 0.5, and 1.0%; n = 4) was added to each dish. Seeds were incubated at 18.3 ± 1.1 °C and monitored

daily for radicle emergence and germination. Total seedling length (combined root and shoot lengths; mm) were recorded on 8- to 10-seedlings from each dish on day 14. Total germination (G) considered the percent germination of all seeds within each dish after 14 days. Time to 50-percent germination (T_{50}) was calculated according to Equation (1):

$$T_{50} = t_i + \frac{\left(\frac{N}{2} - n_i\right) (t_j - t_i)}{(n_j - n_i)} \quad (1)$$

where N is the number of germinated seeds, and n_j and n_i represent the cumulative number of germinants observed during adjacent counts at times t_i and t_j ($n_i < N/2 < n_j$) [23]. Mean germination time (MGT) was calculated according to Equation (2):

$$GT = \frac{\sum Dn}{\sum n} \quad (2)$$

where n is the number of germinated seeds on day D , and D is the number of days counted after initial germination. Germination index (GI) was estimated using the following formula (Equation (3)):

$$GI = \sum \left(\frac{Gt}{Dt} \right) \quad (3)$$

where Gt is the number of germinated seeds on day t , and Dt is the number of germination days [24]. Seed vigor index (VI) was calculated using the equation below (Equation (4)) [24]:

$$VI = G \times L \quad (4)$$

where G is the percentage of seeds germinated, and L is total seedling length (mm).

2.2. Experiment 2—Glasshouse

Tomato seeds (*Solanum lycopersicum* cv. Red Cherry) were placed in gelatin capsules with or without controlled-released fertilizers. Capsules, seeds, fillers, and fertilizers were assembled using a semi-automated filling machine (CN-100M; iPharmachine, Zhejiang, China). Fertilizer treatments involved three levels of controlled-release fertilizers (8-, 16-, and 32-prills; 18:6:8 N:P:K, Florikan with nutricote, Sarasota, FL, USA), which accounted for approximately 400, 800, and 1600 mg fertilizer per capsule, respectively. The encapsulated treatments with 0-, 8-, and 16-prills (C.0, C.8, and C.16, respectively) were placed in standard 00 size capsules (0.9 mL volume) made from bovine bone gelatin (Capsuline Inc., Dania Beach, FL, USA). The 32-prill treatment (C.32) was encapsulated in a larger 000 size capsule (1.4 mL volume), also made of bovine bone gelatin (Xprs Nutra; South Jordan, Utah, USA). The remaining void space for all encapsulated treatments (including without fertilizer; C.0) was loosely filled with a proprietary binder material (Klondike Ag., Akron, OH; US Patent 8,683,742 B1) [20].

In early July, a single control seed (CTRL) or encapsulated seed unit was planted in a 3.4 L polypropylene pot with commercial potting soil (Miracle-Gro all Purpose Potting Mix, Scotts Miracle-Gro Co., Marysville, OH, USA). A total of 50 pots were employed in this study (10 pots per treatment) and were placed in a randomized complete block design that accounted for the north–south orientation of the glasshouse benches [25]. The temperature in the climate-controlled glasshouse was maintained between 25 and 30 °C, with relative humidity fluctuating between 35 and 90%. Plants were watered daily with approximately 400 mL of water.

Seedling emergence (and survival) was monitored daily for the first 2 weeks, and then twice a week through the remaining 8 weeks. In this study, successful seedling emergence was characterized by the presence of aerial cotyledons. Plant height was recorded weekly

(over 9 weeks) beginning 12 days after sowing. Initiation of flower production was also observed within each pot. After nearly 11 weeks, plants were harvested and evaluated for biomass, which involved carefully removing the plants from the pots, sorting between above- and belowground structures, drying in a laboratory oven at 60 °C until constant weight, and then weighing.

2.3. Material and Soil Analyses

Hard gelatin capsules were evaluated for pH and electrical conductivity according to the Gelatin Manufacturers Institute of America's (GMIA) standard testing procedures [26] (n = 5). Commercial potting soil was evaluated for pH and electrical conductivity according to Mylavarapu et al. [27] (n = 4). In addition, soil samples (n = 4) were dried at 80 °C, ground using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA), and passed through a 1 mm mesh screen. Total soil N concentrations were determined using oxygen combustion gas chromatography with an elemental analyzer (NA1500; CE Elantech Instruments; Lakewood, NJ, USA), as described by the Association of Official Analytical Chemists (AOAC) [28]. These samples were also used to evaluate total soil macronutrients (P, K, Ca, Mg, and S) and additional elements (Fe, Mn, Zn, Cu, B, Al, and Na), which involved closed-vessel HNO₃ digestion in a microwave digestion system (MARS 6 Microwaves; CEM Corp; Matthews, NC, USA) according to Campbell and Plank [29]. The digested samples were diluted to 50 mL with deionized water and passed through acid-washed filter paper. Total nutrient concentrations were then determined using inductively coupled plasma–optical emission spectrometry (ICP-OES; Spectro Arcos EOP, Ametek, Mahwah, NJ, USA; see Table 1 for fertilizer, gelatin, and soil physiochemical properties) [30].

Table 1. Physiochemical properties of materials used in this study.

Component	Fertilizer	Gelatin	Soil
pH	5.0 (10% Aq.)	5.72 ± 0.06	6.02 ± 0.12
EC (dS m ⁻¹)	ND	0.15 ± 0.01	2.20 ± 0.10
C (%)	ND	98.5 ± 0.5	45.7 ± 0.37
N (g Kg ⁻¹)	180	162 ± 3.0	9.07 ± 0.09
P (g Kg ⁻¹)	60	ND	1.31 ± 0.05
K (g Kg ⁻¹)	80	0.33 ± 0.05	4.58 ± 0.13
Ca (g Kg ⁻¹)	ND	0.9 ± 0.1	9.87 ± 0.60
Mg (g Kg ⁻¹)	12	ND	0.41 ± 0.32
S (g Kg ⁻¹)	40	ND	1.53 ± 0.06
Fe (g Kg ⁻¹)	2	0.02 ± 0.01	1.98 ± 0.03
Mn (mg Kg ⁻¹)	0.6	ND	97.6 ± 1.61
Zn (mg Kg ⁻¹)	ND	1.5 ± 0.5	16.3 ± 0.24
Cu (mg Kg ⁻¹)	0.5	ND	5.20 ± 0.11
B (mg Kg ⁻¹)	2	ND	4.59 ± 0.06
Al (g Kg ⁻¹)	ND	ND	1.92 ± 0.03
Na (g Kg ⁻¹)	ND	3.6 ± 1.4	0.39 ± 0.01

Data presented include pH, electrical conductivity (EC), and elemental content of fertilizer (Florikan), gelatin (n = 5), and soil (n = 4). Soil and gelatin data are presented as means ± 1 standard error (SE). Note, data are in percentages for carbon content of soil and gelatin. Gelatin elemental composition is based on data from GMIA [26]. Some properties were not determined (ND).

2.4. Data Analyses

Germination data (including percent emergence and number of days until emergence), biomass, and flower production were statistically analyzed to compare the CTRL against encapsulated treatments (C.0, C.8, C.16, and C.32) using generalized linear models (GLMs). When significant treatment responses were found, post-hoc evaluations were performed using least significant difference (LSD) tests.

Due to the longitudinal nature of the plant height data, generalized estimating equations (GEEs) were employed, which are an extension of GLMs designed for repeated-measures analyses [31,32]. GEEs were selected because of the model's ability to evaluate non-normal longitudinal data that are often characteristic of growth data. Wald χ^2 tests were performed on the parameters identified by GEEs that had significant treatment responses. All statistical analyses were conducted using SPSS software version 26 (IBM Corp.), where comparisons were considered significant at $\alpha = 0.05$.

3. Results and Discussion

Based on laboratory tests, there were no significant differences in percent seed germination ($p = 0.97$) or germination index (GI; $p = 0.47$) among the controls and gelatin treatments (Figure 1, panels A and B). There were, however, significant germination delays due to gelatin exposure including an additional 2- to 3-days until 50% germination (T_{50}) for all treatments ($p < 0.001$), and a 1- to 2-day delay in mean germination time (MGT) for seeds exposed to 0.5 and 1.0% gelatin ($p \leq 0.08$; Figure 1, panels C and D). Similarly, when seeds were exposed to gelatin concentrations of 0.5% or higher, there were significant reductions in seedling length after 14 days ($p < 0.001$) and a concomitant decrease in seed vigor ($p < 0.001$; Figure 1, panels E and F). These results are consistent with Touchette and Cox [19], who observed significant delays in T_{50} and MGT, as well as reductions in seedling length and vigor for tomatoes (cv. Cherokee Purple) when gelatin levels were $\geq 0.4\%$. Nevertheless, there were no significant reductions in seedling emergence for gelatin-encapsulated seeds when planted in glasshouse containers ($p = 0.78$; Table 2). However, in agreement with the laboratory results, the container study also revealed a 1- to 2-day delay in emergence for the seeds in the C.0, C.8, and C.32 treatments planted in soil ($p \leq 0.016$; Table 2).

While seedling length and vigor were lower in seeds exposed to $\geq 0.5\%$ gelatin in petri dishes after 14 days, this response was not observed in glasshouse containers with commercial potting soil. That is, 2 weeks after emergence, there were no significant differences in seedling height between the control (CTRL; 15.2 ± 0.7 cm) and treatments (15.0 ± 0.7 cm; $p \geq 0.29$; Figure 2). By 3 weeks after emergence, however, plants from encapsulated seeds with controlled released fertilizers were significantly taller (25.0 ± 0.9 cm for combined C.8, C.16, and C.32 treatments) than those in the CTRL (16.1 ± 0.9 cm) and C.0 treatments (14.8 ± 1.3 cm; $p \leq 0.003$; Figure 2). This increased height of the encapsulated seeds with controlled-released fertilizers continued for the remaining 6 weeks. By the end of this study, the plants from seeds encapsulated with fertilizer were 75.5% taller than the CTRL plants (Figure 2). Moreover, within fertilizer treatments, C.32 plants were significantly taller than C.8 plants after nine weeks ($p \leq 0.001$), but C.16 plants were not found to be significantly different from either C.8 or C.32 plants ($p \leq 0.17$). Interestingly, in this study, the performance of the C.0 plants was similar to the CTRL plants. This was unexpected as previous investigations have demonstrated biostimulatory responses in tomatoes when exposed to plant- or animal- protein hydrolysates [1,19,33,34]. For example, tomato cuttings exposed to plant-based protein hydrolysates produced larger above- and belowground structures after 8 days [33]. Gelatin, an animal-based protein hydrolysate, has also been shown to increase vertical growth, leaf area, above- and belowground plant mass, and fruit production in tomatoes, as well as improved plant performance in arugula, broccoli, corn, cucumber, pepper, and snapdragon [19,21,35,36].

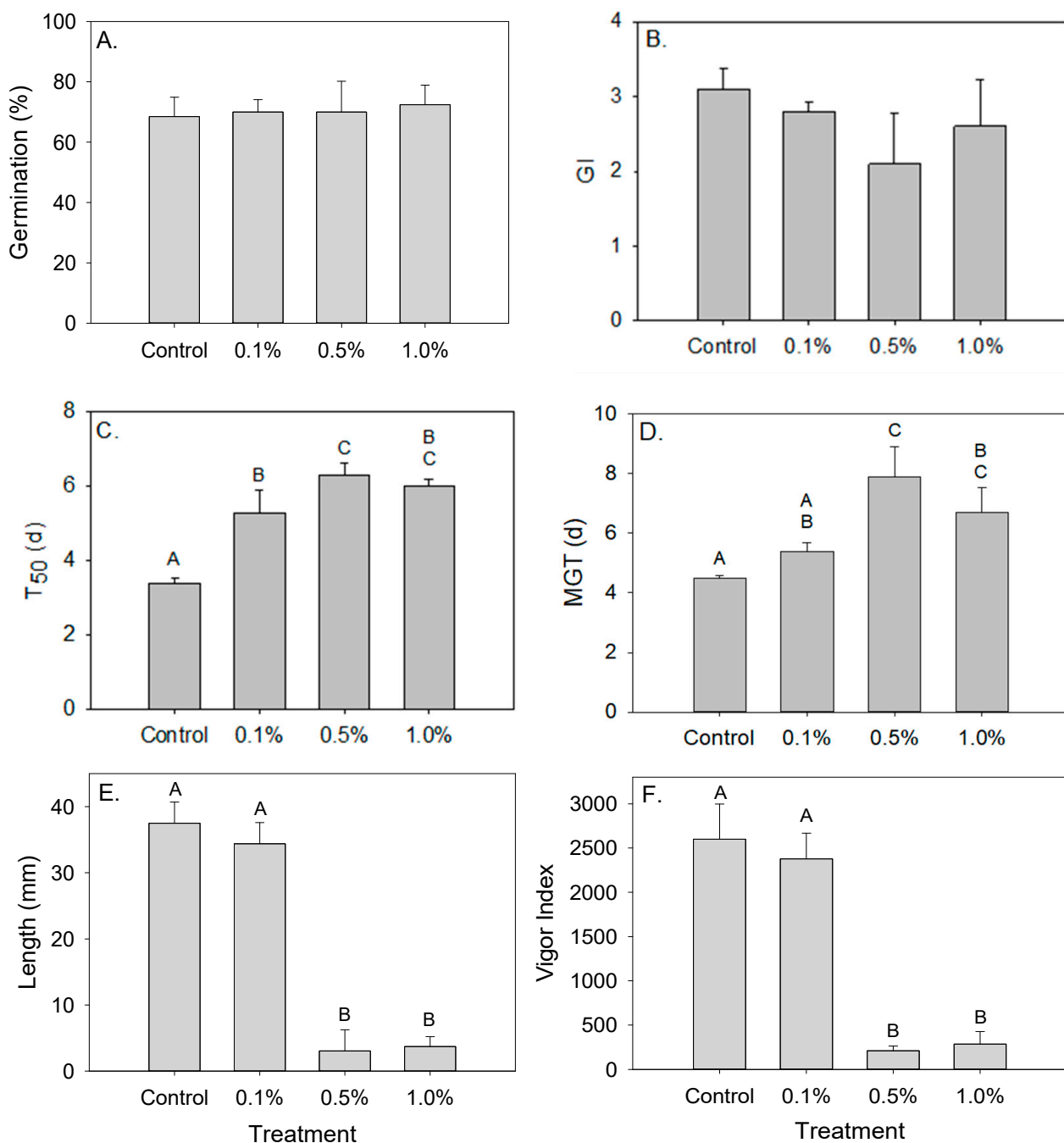


Figure 1. Germination and vigor of tomato seeds (*Solanum lycopersicum*, cv. Red Cherry) in control and treated seeds exposed to different levels of gelatin (0.1, 0.5, and 1.0%). Parameters include percent germination at 14 days (**A**), germination index (GI; **B**), time to 50% germination in days (T₅₀; **C**), mean germination time in days (MGT; **D**), seedling length at day-14 (**E**), and vigor index (**F**). Significant differences among control and treatments, based on generalized linear models (GLMs) followed by least significant difference (LSD) tests for pairwise evaluation, are designated by letters where different letters identify significant differences among treatments (n = 4; α = 0.05). Data are presented as means ± 1 standard error (SE).

Table 2. Tomato (*Solanum lycopersicum*, cv. Red Cherry) growth and performance in glasshouse container experiment.

Parameter	Control	C.0	C.8	C.16	C.32
<i>Germination</i>					
Emergence (%)	90 ± 10	80 ± 13	80 ± 13	90 ± 10	70 ± 15
Emergence (d)	4.1 ± 0.1 ^A	5.7 ± 0.7 ^{BC}	6.8 ± 0.5 ^C	5.1 ± 0.1 ^{AB}	6.6 ± 0.7 ^C
<i>Biomass</i>					
Above (g)	1.09 ± 0.21 ^A	1.12 ± 0.17 ^A	3.79 ± 0.28 ^B	5.19 ± 0.78 ^{BC}	6.19 ± 0.62 ^C
Below (g)	0.82 ± 0.18 ^A	1.12 ± 0.23 ^A	2.73 ± 0.23 ^B	4.60 ± 0.50 ^C	4.69 ± 0.26 ^C
Total (g)	1.91 ± 0.34 ^A	2.24 ± 0.32 ^A	6.52 ± 0.41 ^B	9.79 ± 1.15 ^C	10.87 ± 0.66 ^C
Above:below	1.68 ± 0.39	1.26 ± 0.26	1.45 ± 0.14	1.13 ± 0.17	1.35 ± 0.17
<i>Flowers</i>					
Flower plant ⁻¹	0.1 ± 0.1 ^A	0.0 ^A	0.0 ^A	1.7 ± 0.5 ^B	2.1 ± 0.8 ^B
Flower (wk)	9.0	ND	ND	6.4 ± 0.6	6.2 ± 0.4
% Flower	10 ± 10 ^A	0.0 ^A	0.0 ^A	70 ± 15.2 ^B	50 ± 16.6 ^B

Data include percent emergence, number of days (d) to emergence, dry biomass (aboveground, belowground, total, and above:below mass ratio), number of flowers per plant, number of weeks (wk) to first flower induction, and the percent of plants that flowered at 9-weeks. Some treatments did not produce flowers, so no data (ND) are reported. Data are presented as means ± 1 standard error (SE; n = 10) for control (CTRL) and experimental treatments with 0 (C.0), 8 (C.8), 16 (C.16), and 32 (C.32) controlled-release fertilizer prills. Significant differences among control and treatments, based on generalized linear models (GLMs) followed by least significant difference (LSD) tests for pairwise evaluation, are designated by different letters ($\alpha = 0.05$).

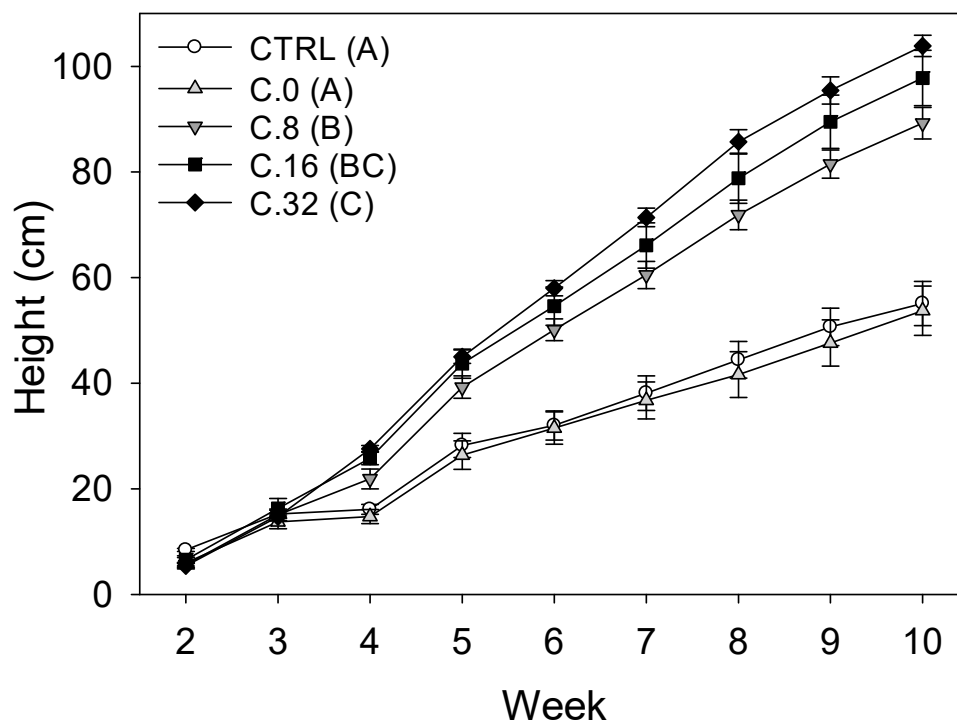


Figure 2. Plant height (*Solanum lycopersicum*, cv. Red Cherry) over time for control (CTRL) and encapsulated treatments including capsule only (C.0), and capsules with controlled-released fertilizers comprising 8- (C.8), 16- (C.16), or 32-fertilizer prills (C.32). Significant differences among the treatments, based on generalized estimating equations (GEEs) for repeated measures, are identified by letters adjacent to the figure legend, where different letters identify significant differences among treatments (n = 10; $\alpha = 0.05$). Data are presented as means ± 1 standard error (SE).

As with height, above- and belowground biomasses were significantly greater in plants germinated from encapsulated seeds with fertilizers (C.8, C.16, and C.32) compared to CTRL and C.0 plants ($p \leq 0.005$ and 0.002 for above- and belowground mass, respectively; Table 2). This included 248, 376, and 467 % increases in aboveground biomass of the C.8,

C.16, and C.32 treatments, respectively. Belowground biomass was notably larger in plants grown from seeds encapsulated with ≥ 16 prills ($p \leq 0.001$). In that case, belowground dry mass was between 460 and 472% larger than CTRLs. These results are consistent with previous studies, where seeds encapsulated with fertilizers had greater biomass than seed-only controls [19,21]. Furthermore, in a study involving gelatin-based controlled released fertilizers, Pulat and Saglam [37] observed increased growth in both tomato and cucumber with increasing amounts of infused NH_4NO_3 . In that study, however, the gelatin-based fertilizer was not adjacent to the seed at the time of planting. For tomatoes, vegetative dry mass accumulation is essential as it is directly proportional to fruit production. That is, the dry mass ratio between the sink strength of the vegetative component and the sink strength of the fruit tends to approach 3.0 [38]. Therefore, if the observed increase in above- and belowground biomass in tomatoes grown from seeds encapsulated with controlled-released fertilizers continues, it would be expected that larger plants would likely produce higher fruit yields.

Faster vertical growth, along with greater biomass, resulted in earlier flower production for the plants grown from seeds encapsulated with fertilizers. In this study, initial flower induction began as early as 6 weeks after germination for C.16 and C.32 plants, compared to 9 weeks in CTRLs (Table 2). By 9 weeks, 70% of C.16 plants had flowered whereas only 10% of the CTRL plants had flowered. In another study involving tomato seed encapsulation with fertilizers, flower production began at 9 weeks, with more flowers produced over time on the plants from seeds encapsulated with controlled-released fertilizers [21]. In that study, however, only two prills were added to each capsule. The results from this study suggest that by placing greater volumes of controlled-fertilizers via seed encapsulation, flowering times can be shortened by nearly 3 weeks. What is particularly notable about these results is that fertilizers can be planted simultaneously with seeds without appreciable signs of phytotoxicity (aside from a 1–2-day delay in germination) associated with the proximity of tomato seeds/seedlings and controlled-release fertilizers. This response may be attributed to optimal nutrient release rates by the fertilizer, as well as the physical separations/barriers placed between the seed and fertilizer.

Agricultural practices often involve excessive nutrient use with a concomitant decrease in fertilizer use efficiency [39]. This approach fosters elevated nutrient leaching and runoff from agricultural lands that may severely degrade natural ecosystems including eutrophication of receiving waters [40,41]. In contrast, controlled-released fertilizers supply nutrients to developing plants at a rate that coincides with their specific nutrient demands [39,42]. Controlled-release fertilizers, therefore, can improve fertilizer use efficiency and lessen overall environmental impacts [43]. Most controlled-released fertilizers are composed of coatings that act as diffusion barriers around organic or inorganic materials [39]. The commercially available fertilizer used in this study contained a resin coating placed around nutrients and proprietary chemical-release agents. Small pores within the coat allow water to enter the prill and release nutrients at a rate that is proportional to both moisture availability and soil temperature (pore size increases at higher temperatures; release rates are based on soil temperatures around 27 °C). The cost to manufacture controlled-released fertilizer, however, is considerably higher than conventional inorganic fertilizers and does pose a realistic obstacle for the widespread adoption of these fertilizers [39,42]. This study, nevertheless, found significant improvements in plant vigor with the direct placement of comparatively small amounts of controlled-released fertilizer. This improved plant performance, along with less fertilizer use, may help offset the high cost typically associated with controlled-released fertilizers.

As mentioned, encapsulation can be viewed as a form of seed coating that generally comprises pelleting, encrusting, or film coatings [21,44,45]. Nevertheless, applying dry

powder coatings to seeds often results in poor dosing, uniformity loss, and dust formation. Moreover, thick coats may break or disintegrate prior to planting [44–46]. Similarly, film coatings on seed surfaces tend to be thinly applied and may not be able to deliver sufficient dosage of plant-benefitting material(s) [45]. This study employed an alternative approach, where pharmaceutical capsules were used to combine seeds with controlled-release fertilizers. The use of gelatin-based capsules provides several unique advantages, including the ability of gelatin to act as a plant-growth stimulator (observed in some studies) and its overall biodegradability following planting; additionally, gelatin-based capsules are readily available commercially. Encapsulation provides similar advantages to other coatings (e.g., uniformity, inclusion of soil microbes, limiting agrochemical exposure), but can also provide the necessary space for greater volumes (including multiple types) of plant-benefitting materials while allowing for a small separation or barrier between potentially phytotoxic agrochemicals and seeds. Indeed, Scott [10] considered the possibility and significance of delivering nutrients through seed coatings, and recognized the value of slowing release rates of fertilizers that would better promote nutrient efficiency in plants. The author also noted that, although nutrient release rates can be engineered using controlled-release technology, it had not been successfully implemented using seed coatings. To our knowledge, this is the first study to investigate the effect of encapsulating tomato seeds with as much as 1600 mg of controlled-release fertilizer, demonstrating improved plant performance including accelerated flower induction by almost 3 weeks. It is possible that seed encapsulation can be an effective tool in delivering fertilizers to crops in a manner that would reduce overall fertilizer application rates when planted in commercial-grade potting mix. Further research is necessary to establish the best ways to utilize this technology, especially its potential role in enhancing plant productivity while reducing overall fertilizer usage in crops.

4. Conclusions

The results of this study support the notion that seed encapsulation with fertilizers can improve tomato seedling performance, as indicated by enhanced vertical growth and greater dry mass production for at least the first 2 months following emergence. In addition, higher levels of controlled-release fertilizers (≥ 800 mg) were able to accelerate flower induction by 3 weeks. Although gelatin exposure delayed germination by 2- to 3- days, the subsequent accelerated seedling growth was able to mitigate this delay. Moreover, the diminished seed vigor observed for higher levels of gelatin ($\geq 0.5\%$) was not apparent in glasshouse container studies involving encapsulated tomato seeds planted in commercial grade soils. Overall, the results of this study suggest that seed encapsulation, using gelatin capsules, can be an effective means to deliver plant-benefitting agrochemicals such as controlled-released fertilizers. Through encapsulation, seeds and other components can be delivered as a single planting unit at the time of sowing. While similar to seed coatings, encapsulation allows for greater volumes and/or multiple types of plant-benefitting materials. Moreover, capsules can promote better uniformity of seeds, allowing for easy adaptation to existing mechanical planters. Therefore, seed encapsulation may provide unique advantages that are not typically offered by other forms of seed coatings and enhancements. While this technology is still developing, future studies involving fertilizer optimization for tomatoes (and other crops), including altering nutrient release rates, may offer additional improvements in plant growth and performance. Similarly, studies involving other forms of agrochemicals (e.g., systemic pesticides) and/or soil microbes may provide novel insights into the benefits of seed encapsulation beyond nutrients.

Author Contributions: Conceptualization, B.W.T. and D.S.C.; methodology, B.W.T. and D.S.C.; validation, B.W.T. and D.S.C.; formal analysis, B.W.T., D.S.C., R.L.C. and H.P.; investigation, B.W.T.,

D.S.C., R.L.C. and H.P.; resources, B.W.T. and D.S.C.; data curation, B.W.T.; writing—original draft preparation, B.W.T.; writing—review and editing, B.W.T., D.S.C. and H.P.; visualization, B.W.T. and D.S.C.; supervision, B.W.T. and D.S.C.; project administration, B.W.T.; funding acquisition, D.S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: We are grateful for the generous support provided by the laboratory staff at NC DACS Division of Agronomic Services who helped with soil nutrient analyses. We are also grateful for the insightful comments and editorial suggestions provided by F. Sundstrom and two external reviewers on earlier versions of this manuscript.

Conflicts of Interest: Klondike Agriculture Products provided the necessary materials (capsules and binder material) to complete this study. As D.S.C. was an employee of Klondike Agricultural Products, B.W.T. (as an outside investigator) was responsible for design of this study; for the collection, analyses, and interpretation of data; for the writing of this manuscript; and in the decision to publish the results.

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