

Original Research Article

Modulation of Seed Germination, Seedling Vigour and Early Growth of *Capsicum annum* L. Seedlings by Arginine Seed Priming and Foliar Application

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Abstract

Seed priming and foliar application of amino acids offer a sustainable route to improve seed performance and early seedling vigour in vegetable nurseries. This study evaluated arginine (Ag) for enhancing seed germination and early seedling growth in *Capsicum* (*Capsicum annum* L. cv. Indra). Seeds were treated for 60 min with Ag at 25–300 ppm and compared with water (control) in a randomised pro-tray experiment conducted in a naturally ventilated polyhouse over two seasons (2024–25 and 2025–26). Germination, germination energy, shoot and root length, seedling fresh and dry weight, total chlorophyll and seedling vigour indices were recorded. All Ag concentrations improved germination and seedling traits over the control, and the 200 ppm treatment performed best: germination reached 98.16 % (control 81.00 %), germination energy increased 5.9-fold, shoot and root length by 1.92- and 1.94-fold, seedling fresh and dry weight by 2.06- and 1.61-fold, total chlorophyll by 1.63-fold, and seedling vigour indices I and II by 2.34- and 1.90-fold, respectively. At 100–300 ppm, Ag also gave significantly higher germination, germination energy and vigour indices than arginine at 25 ppm. Responses declined at 250–300 ppm, indicating a concentration optimum. Seed priming and foliar application with 200 ppm Ag is therefore a promising, eco-friendly approach for producing vigorous *Capsicum* seedlings.

Keywords: Arginine, Seed priming, *Capsicum annum*, Seedling vigour, Sustainable horticulture.

1. Introduction

Capsicum (*Capsicum annuum* L.), commonly known as bell pepper, belongs to the family Solanaceae. Its fruits are a valuable source of vitamin C (150–180 mg per 100 g), vitamin A, potassium, phosphorus, magnesium and calcium [1,2], and their bioactive constituents have been associated with protective effects against cardiovascular disorders, cancer and hypercholesterolaemia [3]. Global acreage and production of *Capsicum* are estimated at 1.99 million hectares (Mha) and 38.02 million tonnes (Mt), respectively, with China and Mexico as the leading producers [4]; in India the crop occupies about 0.042 Mha with a production of 0.66 Mt [5]. Raising healthy, uniform seedlings is the first step towards a productive *Capsicum* crop. Priming and foliar application are simple, low-cost techniques that hasten germination, improve uniformity and promote vigorous seedling growth in vegetable crops [6,7].

Conventional crop-input strategies rely on inorganic fertilizers and agrochemicals [8], whose indiscriminate use raises concerns about residues, human health and environmental safety [9]. Attention has therefore turned to bio-based seed priming and foliar application have been shown to improve seed vigour and early seedling establishment [10,11]. Amino acids are the building blocks of proteins and influence cellular processes such as growth, stress resistance and metabolism [12], which makes them attractive active ingredients for such formulations.

Arginine, in particular, is a nitrogen-rich amino acid that serves as a major nitrogen reserve and as a precursor of polyamines and nitric oxide [13,14]. Seed priming with arginine has been reported to improve germination or growth in pepper and wheat [14–16], and foliar arginine improved tomato growth, yield and fruit quality [17]. To our knowledge, however, arginine has not been evaluated as a seed priming and as a foliar application in *Capsicum*. The present study therefore aimed to evaluate a range of concentrations (25–300 ppm) of an arginine (Ag) against control (water) for effects on seed germination, seedling growth, biomass, chlorophyll content and seedling vigour of *Capsicum* in a pro-tray bioassay over two seasons.

2. Materials and Methods

2.1 Experimental Site and Plant Material

The investigation was carried out at the Department of Horticulture, Rajasthan Agricultural Research Institute (Sri Karan Narendra Agriculture University, Jobner), Durgapura, Jaipur, Rajasthan, India (26°51' N, 75°47' E; 390 m above mean sea level; agro-climatic zone III-a, semi-arid eastern plain). Seedling experiments were

conducted during the kharif seasons of 2024–25 and 2025–26 in a naturally ventilated polyhouse using *Capsicum* cv. Indra. Laboratory analyses were performed in the Department of Horticulture, SKN College of Agriculture, Jobner.

2.2 Seedling Bioassay

Seeds of *Capsicum annuum* L. cv. Indra were treated for 60 min with one of eight treatments: water (control) and Ag at 25, 50, 100, 150, 200, 250 and 300 ppm (w/v). Following treatment, the seeds were sun-dried and sown in pro-trays containing cocopeat, perlite and vermiculite in a 3:1:1 ratio under polyhouse conditions. In addition to seed treatment, two foliar applications of the respective Ag treatments were applied at 15 and 25 days after sowing (DAS). The experiment followed a randomized block design (RBD) with three replications, with 100 seeds per treatment in each replication (300 seeds per treatment), and was repeated in two successive seasons following standard seed-testing procedures [18].

2.3 Observations

Germination was counted at 5-day intervals up to 30 days after sowing (DAS). Germination (%) at 30 DAS was calculated as (germinated seeds/total seeds sown) $\times$ 100. Mean daily germination (MDG) was calculated as germination (%) divided by the total number of experimental days (30) [19], and germination energy (GE) as the percentage of seeds germinated by the 15th day [20]. Growth parameters were recorded at 30 DAS on 10 seedlings per replicate. Shoot and root lengths were measured with a scale (cm), and relative root elongation (RRE, %) was calculated as (mean root length of treated seedlings/mean root length of control) $\times$ 100 [20].

Fresh weight was recorded on a precision balance (Saftron SES200) after washing the roots free of medium, and dry weight after shade-drying to constant weight. Total chlorophyll was determined by the dimethyl sulfoxide (DMSO) method [21]: 50 mg of leaf tissue was incubated in 5 mL DMSO at 65 °C for 4 h in the dark, absorbance was read at 663, 645 and 480 nm against a DMSO blank, and chlorophyll a and b were calculated from A663 and A645, summed and expressed as mg g⁻¹ fresh weight (FW). Seedling vigour indices were calculated as SVI-I = germination (%) $\times$ seedling length (shoot + root, cm) and SVI-II = germination (%) $\times$ seedling dry weight (mg) [22].

2.4 Statistical Analysis

Data were analysed using JMP version 18 [23] and treatment means were separated by the Tukey–Kramer hon-

Table 1. Effect of Ag on germination percentage, mean daily germination (MDG) and germination energy (GE) of Capsicum at 30 DAS.

Treatment	Germination (%)	MDG	GE (%)
Control (water)	81.00 ± 0.78f	2.69 ± 0.017e	3.99 ± 0.88f
Ag (ppm)			
25	86.83 ± 0.77e	2.89 ± 0.017d	10.66 ± 0.72e
50	90.66 ± 0.72d	3.02 ± 0.020c	13.83 ± 0.88d
100	93.49 ± 0.88bc	3.11 ± 0.025bc	16.49 ± 0.49c
150	92.50 ± 0.57c	3.08 ± 0.008bc	17.00 ± 0.57c
200	98.16 ± 0.45a	3.26 ± 0.008a	23.66 ± 0.72a
250	94.50 ± 0.57b	3.14 ± 0.011b	20.50 ± 0.57b
300	91.99 ± 0.60cd	3.06 ± 0.034bc	17.49 ± 0.88c

Values are two-season means ± SE of three replicates of 100 seeds. Means followed by the same letter within a column do not differ significantly (Tukey–Kramer HSD, $p = 0.05$).

Table 2. Effect of Ag on germination percentage, mean daily germination (MDG) and germination energy (GE) of Capsicum at 30 DAS.

Treatment	Germination (%)	MDG	GE (%)
Control (water)	81.00 ± 0.78f	2.69 ± 0.017e	3.99 ± 0.88f
Ag (ppm)			
25	86.83 ± 0.77e	2.89 ± 0.017d	10.66 ± 0.72e
50	90.66 ± 0.72d	3.02 ± 0.020c	13.83 ± 0.88d
100	93.49 ± 0.88bc	3.11 ± 0.025bc	16.49 ± 0.49c
150	92.50 ± 0.57c	3.08 ± 0.008bc	17.00 ± 0.57c
200	98.16 ± 0.45a	3.26 ± 0.008a	23.66 ± 0.72a
250	94.50 ± 0.57b	3.14 ± 0.011b	20.50 ± 0.57b
300	91.99 ± 0.60cd	3.06 ± 0.034bc	17.49 ± 0.88c

Values are two-season means ± SE of three replicates of 100 seeds. Means followed by the same letter within a column do not differ significantly (Tukey–Kramer HSD, $p = 0.05$).

estly significant difference (HSD) test at $p = 0.05$. Values are presented as means ± standard error (SE) of the two seasons.

3. Results

3.1 Seed Germination

No germination occurred at 5 DAS in any treatment, and germination began at 10 DAS (Table 1). At every observation, all Ag concentrations recorded significantly more germinated seeds than the control. At 10 DAS, Ag gave 5.83–12.83 germinated seeds per 100 against 1.16 in the control. The 200 ppm treatment led at every stage, with 12.83, 23.66, 93.83 and 98.16 seeds per 100 at 10, 15, 20 and 30 DAS, respectively, compared with 1.16, 3.99, 70.16 and 81.00 in the control.

Final germination at 30 DAS ranged from 86.83 to 98.16 % across Ag concentrations, against 81.00 % in the control (Table 2). Mean daily germination (2.89–3.26 versus 2.69 in the control) and germination energy (10.66–

23.66 % versus 3.99 %) followed the same pattern. Ag at 200 ppm gave the highest values for all three (98.16 %, 3.26 and 23.66 %), a 1.21-fold increase in germination and a 5.9-fold increase in germination energy over the control.

3.2 Shoot and Root Growth

Shoot length increased from 6.4 cm in the control to 7.7–12.3 cm across Ag concentrations, and root length from 8.7 to 11.2–16.9 cm (Table 3). At 150–250 ppm both traits were significantly greater than with control, with the maximum at 200 ppm (shoot 12.3 cm, 1.92-fold; root 16.9 cm, 1.94-fold over the control). Relative root elongation reached 193 % at 200 ppm and ranged from 150 to 193 % at 150–300 ppm, against 100 % with control.

3.3 Biomass and Chlorophyll Content

Seedling fresh weight was highest at 200 and 250 ppm (0.817 and 0.793 g), about twice the control (0.396 g)

Table 3. Effect of Ag foliar application on fresh weight, dry weight and total chlorophyll content of Capsicum seedlings at 30 DAS.

Treatment	Fresh weight (g)	Dry weight (g)	Total chlorophyll (mg g ⁻¹ FW)
Control (water)	0.396 ± 0.014f	0.061 ± 0.001e	1.36 ± 0.011f
Ag			
25	0.564 ± 0.014cde	0.082 ± 0.001cd	1.78 ± 0.016e
50	0.556 ± 0.012cde	0.084 ± 0.001bcd	1.87 ± 0.013cd
100	0.643 ± 0.015cd	0.086 ± 0.002bc	1.90 ± 0.012cd
150	0.675 ± 0.016bc	0.091 ± 0.002ab	1.95 ± 0.011c
200	0.817 ± 0.016a	0.098 ± 0.001a	2.21 ± 0.012a
250	0.793 ± 0.017ab	0.095 ± 0.002a	2.10 ± 0.012b
300	0.658 ± 0.017cd	0.087 ± 0.001bc	1.89 ± 0.015cd

Values are two-season means ± SE of three replicates of 10 seedlings. Means followed by the same letter within a column do not differ significantly (Tukey–Kramer HSD, $p = 0.05$). FW, fresh weight.

Table 4. Effect of Ag foliar application on fresh weight, dry weight and total chlorophyll content of Capsicum seedlings at 30 DAS.

Treatment	Fresh weight (g)	Dry weight (g)	Total chlorophyll (mg g ⁻¹ FW)
Control (water)	0.396 ± 0.014f	0.061 ± 0.001e	1.36 ± 0.011f
Ag			
25	0.564 ± 0.014cde	0.082 ± 0.001cd	1.78 ± 0.016e
50	0.556 ± 0.012cde	0.084 ± 0.001bcd	1.87 ± 0.013cd
100	0.643 ± 0.015cd	0.086 ± 0.002bc	1.90 ± 0.012cd
150	0.675 ± 0.016bc	0.091 ± 0.002ab	1.95 ± 0.011c
200	0.817 ± 0.016a	0.098 ± 0.001a	2.21 ± 0.012a
250	0.793 ± 0.017ab	0.095 ± 0.002a	2.10 ± 0.012b
300	0.658 ± 0.017cd	0.087 ± 0.001bc	1.89 ± 0.015cd

Values are two-season means ± SE of three replicates of 10 seedlings. Means followed by the same letter within a column do not differ significantly (Tukey–Kramer HSD, $p = 0.05$). FW, fresh weight.

(Table 4). Dry weight followed a similar trend, with 150–250 ppm giving 0.091–0.098 g against 0.061 g in the control. Total chlorophyll was significantly higher than the control in all Ag treatments (1.78–2.21 versus 1.36 mg g⁻¹ FW), peaking at 200 ppm (2.21 mg g⁻¹ FW; 1.63-fold over the control).

3.4 Seedling Vigour Indices

SVI-I increased from 1227 in the control to 1649–2870 with Ag, and SVI-II from 5085 to 7163–9669 (Table 5). Both indices were maximal at 200 ppm (2.34- and 1.90-fold over the control), and every Ag treatment had a significantly higher SVI-II than control; SVI-I was significantly higher than with control at 100–300 ppm. Vigour declined at 250 and 300 ppm but remained above the control. The 200 ppm treatment recorded the highest value for every trait in both seasons.

4. Discussion

4.1 Seed Priming Response and Dose Dependence

Seed priming and foliar application of Ag accelerated and improved germination and enhanced seedling growth, biomass, chlorophyll content and vigour in Capsicum, with the strongest effects at 200 ppm in both seasons. Germination is a decisive stage for crop establishment, and priming improves the speed and uniformity of germination through controlled hydration and early metabolic activation [6,7]. The improvement observed here is in line with reports that seed priming and foliar application enhance seed vigour and early seedling establishment [10,11]. The response was concentration dependent: values rose up to 200 ppm and declined at 250 and 300 ppm, although they stayed above the untreated control. For fresh and dry weight, 250 ppm did not differ significantly from 200 ppm (Table 4), so the biomass optimum spans 200–250 ppm, whereas

Table 5. Effect of Ag on seedling vigour indices (SVI-I and SVI-II) of Capsicum.

Treatment	SVI-I	SVI-II
Control (water)	1227 ± 47.3g	5085 ± 20.1g
Ag (ppm)		
25	1649 ± 36.8ef	7163 ± 28.2f
50	1717 ± 27.3e	7662 ± 21.3e
100	1940 ± 28.5d	8088 ± 23.6d
150	2054 ± 32.8c	8371 ± 23.6c
200	2870 ± 21.3a	9669 ± 23.6a
250	2438 ± 21.9b	8977 ± 15.8b
300	2050 ± 29.1cd	8048 ± 26.5d

SVI-I = germination (%) × seedling length (cm); SVI-II = germination (%) × seedling dry weight (mg). Values are two-season means ± SE. Means followed by the same letter within a column do not differ significantly (Tukey–Kramer HSD, $p = 0.05$).

germination, growth and vigour peaked sharply at 200 ppm. Optimum-type responses of this kind have been noted for seed priming and underline the need to calibrate dose [10].

4.2 Role of Arginine

Arginine is a major nitrogen reserve in plants: its high nitrogen-to-carbon ratio makes it a readily mobilizable source of nitrogen for the growing embryo, and it is a precursor of polyamines and nitric oxide, which take part in hormonal and redox signalling [13,14]. Exogenous arginine has been reported to promote seed energy metabolism and germination in wheat [14], and it has improved the growth and physiological performance of wheat, maize and fenugreek, mainly under water deficit [16,24,25]. The faster germination, greater germination energy and higher chlorophyll content of Ag treated seedlings are consistent with these roles, although arginine uptake, nitrogen status and signalling were not measured in this study.

Arginine at 25 ppm improved germination (86.83 versus 81.00 % in the control) and seedling vigour (SVI-II 7163 versus 5085), in agreement with reported benefits of arginine priming in pepper [15]. However, Ag at 100–300 ppm gave significantly higher germination, germination energy and both vigour indices than control, and at 200 ppm it produced 1.13-fold higher germination, 2.2-fold higher germination energy, 1.58- and 1.51-fold longer shoots and roots, 1.45-fold higher fresh weight, 1.24-fold higher chlorophyll and 1.35-fold higher SVI-II than 25 ppm arginine. At 50 ppm, in contrast, Ag did not differ significantly from 25 ppm arginine for shoot length, root length, fresh weight or dry weight, so the advantage of the formulation emerged mainly at higher concentrations. Seed priming have been proposed to improve the delivery of active molecules to the seed [10], which

could explain the greater efficacy of the formulation; however, uptake and release were not measured here, so this explanation remains to be tested.

4.3 Practical Implications and Limitations

Treating seeds with 200 ppm Ag for 60 min raised germination above 98 % and produced markedly more vigorous, chlorophyll-rich seedlings in pro-trays, which is directly relevant to nursery production of Capsicum. The study is limited to one cultivar, one growing medium and a 30-day observation window, and the proposed mechanisms are inferred from the literature rather than measured directly. Further work should examine transplant establishment and yield, other cultivars and media, uptake and release of arginine, enzymatic and hormonal responses, and environmental safety.

5. Conclusion

Seed priming and foliar application with the arginine (Ag) significantly improved seed germination and early seedling growth of Capsicum over two seasons. All concentrations from 25 to 300 ppm improved germination, growth, biomass, chlorophyll content and vigour compared with the untreated control, and 200 ppm was the optimum, giving 98.16 % germination and 2.34- and 1.90-fold higher SVI-I and SVI-II. Ag at 100–300 ppm also outperformed 25 ppm arginine for germination and vigour. Ag seed priming is therefore a promising bio-based option for producing vigorous Capsicum seedlings, and its effects on transplant establishment, yield and the mechanisms involved merit further study.

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