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Physiological and biochemical responses of palak (*Beta vulgaris* var. *bengalensis*) seeds to TNAU Vidhai Amirtham biopolymer coating

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Abstract

Palak (*Beta vulgaris* var. *bengalensis*), an important leafy vegetable, may exhibit poor and non-uniform germination. Seed coating with a bio-based polymer offers a low cost seed enhancement approach. A laboratory experiment was carried out at the Department of Seed Science and Technology, Tamil Nadu Agricultural University (TNAU), Coimbatore, to standardise the polymer-to-water ratio of TNAU Vidhai Amirtham, for Palak cv. All Green. Seeds were coated with 7, 8, 9 and 10 g polymer combined with 40, 50 and 60 mL water resulting twelve treatments along with hydropriming and untreated control with four replications in a completely randomised design (CRD) The 7 g polymer + 60 mL water treatment (T_3) recorded the highest germination (94 %), germination speed (9.81), root length (10.6 cm), shoot length (7.0 cm), vigour index I (1654) and vigour index II (0.658), significantly exceeding the untreated control, representing improvements of 34.3 % in germination and 96.9 % in vigour index I over the untreated control. T_3 also recorded the highest α-amylase activity (2.789) and dehydrogenase activity (1.921 OD), consistent with enhanced metabolic activity and reserve mobilisation during germination. Catalase and peroxidase activities showed no significant treatment effect, suggesting that antioxidant enzyme responses were not major determinants of the observed treatment differences. These results identify 7 g polymer + 60 mL water as the most effective TNAU Vidhai Amirtham coating combination for improving physiological and biochemical seed quality in palak, suggesting its potential as a low-cost, chemical-free seed enhancement strategy for improving field establishment and stand uniformity in leafy vegetable nurseries and seed production systems.

Keywords: enzyme activity; germination; palak; seed coating; TNAU Vidhai Amirtham

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Introduction

Palak (*Beta vulgaris* var. *bengalensis*), widely known as spinach beet, is among the most widely cultivated leafy vegetables in the Indian subcontinent, valued for its rapid growth cycle, year-round availability and high nutritive content, with 100 g of edible leaves reported to contain 5862 IU of vitamin A, 70 mg of vitamin C, 380 mg of calcium and 16 mg of iron (1). Despite its short crop duration and wide adaptability, commercial cultivation of palak is frequently constrained by poor field emergence, non-uniform stand establishment and slow initial seedling vigour, particularly when seeds are sown directly under variable moisture and temperature conditions (2). Early crop establishment is an important determinant of plant population and subsequent crop performance; therefore, seed enhancement technologies that improve the speed and uniformity of germination may provide practical benefits for crop establishment (3).

Seed coating is a well-established seed enhancement technique in which seeds are enveloped in a thin, uniform layer of polymer, along with nutrients, biostimulants or protectants, without materially altering seed shape while improving handling, sow ability and physiological performance (4). Polymer based coatings function primarily by improving imbibition uniformity, providing a protective microenvironment around the seed and, in the case of nutrient or biostimulant

enriched formulations, actively triggering metabolic activation of reserve mobilising enzymes during early germination (5). Coating technologies that incorporate micronutrients or biostimulants have been reported to elevate the activity of amylase and antioxidant enzymes and improve early seedling vigour across a range of horticultural crops especially crop like cucumber, such treatments may also enhance enzymes involved in reserve mobilisation, including α-amylase and protease (6). Similarly, nutrient enriched film coatings have been reported to significantly improve germination and promote dehydrogenase activity during seed germination in vegetable crops, where coated seeds showed improved germination for poor quality seed lots (7).

The TNAU Vidhai Amirtham is a seed coating polymer formulation developed at the Seed Centre, Department of Seed Science and Technology (DSST), Tamil Nadu Agricultural University (TNAU), Coimbatore, as an indigenous seed-enhancement product for field and vegetable crops. While the exact proprietary formulation of TNAU Vidhai Amirtham is not disclosed, available scientific evaluations and institutional documentation indicate that it comprises a water-soluble or water-dispersible film-forming polymer matrix that binds nutrients and micro-agents uniformly to the seed coat while permitting adequate oxygen exchange (8). This polymer base is combined with plant growth-promoting compounds, including root-promoting phytohormone-like agents intended to hasten emergence and alleviate mild dormancy, along with micronutrients such as zinc and other trace elements to support early embryonic root and shoot development (8). In direct-seeded rice, seeds treated with TNAU Vidhai Amirtham at 25 mL kg^{-1} substantially improved field emergence, root volume, productive tiller number, panicle length and final seed yield compared with untreated seed under both puddled and dry direct-seeded conditions (8). In a separate study on machine transplanted rice, coating with Vidhai Amirtham combined with hydro priming was found to improve seedling quality traits suitable for machine transplanting (9). However, despite these encouraging results in cereal crops, no published information is currently available on the performance of TNAU Vidhai Amirtham in leafy vegetable seeds such as palak, nor on the optimum polymer to water ratio required for this crop.

The efficacy of seed-coating polymer can depend on polymer concentration, dilution ratio and coating characteristics; therefore, formulation standardisation is important before recommending a coating for a specific crop and seed type. Therefore, the present investigation was conducted to standardise the TNAU Vidhai Amirtham polymer to water ratio for Palak cv. All Green and to evaluate its effects on physiological (Speed of germination, Germination (%), root length, shoot length, vigour index I and II) and biochemical (α amylase, dehydrogenase, catalase and peroxidase) attributes with seed germination and seedling vigour.

Materials and Methods

Source of planting material

The experiment was conducted at the Department of Seed Science and Technology, Tamil Nadu Agricultural University, Coimbatore, India. Seeds of palak (*B. vulgaris* var. *bengalensis*) cv. 'All Green' were procured from the Department of Vegetable Science, TNAU, Coimbatore. Liquid polymer formulation, TNAU Vidhai Amirtham, was sourced from the Seed Centre, TNAU, Coimbatore and was used for seed coating.

Seed coating treatments and experimental design

The TNAU Vidhai Amirtham polymer was diluted with distilled water at specified proportions and uniformly applied to a known 25 g of seeds using a laboratory rotary seed coater operated at 30 rpm for 5 min ensuring uniform distribution of polymer water suspension across the seed surface. Following coating, seeds were oven dried at 30 °C for 30 min and uniform seed coating have been ensured by visual examination and the dried seeds have been directly used for physiological and biochemical analysis. The experiment comprised 14 treatments, including 12 dose combinations of polymer (7, 8, 9 and 10 g) and water (40, 50 and 60 mL), which were evaluated against untreated control. The treatment combinations were structured as follows:

Evaluation of physiological seed quality parameters

The germination speed was evaluated in four replications of 100 seeds each. Germinated seeds displaying radicle protrusion (≥ 2 mm) were recorded regularly from the first day to final count (14 days). Germination speed was computed according to standard formula proposed by previously (10):

$$\text{Germination speed} = \sum ni / ti \qquad \text{Eq. 1}$$

Where,

ni - no of seeds germinated on day ti

ti - no of days from the start of the test.

Germination percentage was determined by the roll towel method as per ISTA (2007) standards (11) and germination percentage was arcsine transformed prior to statistical analysis. Root and shoot length were measured from the point of seed attachment to the root tip and leaf tip, respectively and expressed in cm. The measurements were recorded from 10 randomly selected normal seedlings per replication at the final count. Dry matter production (DMP) was measured using the same 10 seedlings taken for root and shoot length measurement. Measuring DMP, seedlings were shade dried for 24 hr followed by 48 hr oven drying at 85 °C, cooled in desiccator for 30 min and weighed; DMP were expressed as g per 10 seedlings. Vigour index I and II were computed using the formulae given by Abdul Baki and Anderson (12) as follows:

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Treatments	Description
Control	Untreated seed
Hydropriming 2 hr	Seeds soaked in water for 2 hr (seed to water ratio of 1 : 1)
T_1	Seed coating with 7 g polymer + 40 mL water
T_2	Seed coating with 7 g polymer + 50 mL water
T_3	Seed coating with 7 g polymer + 60 mL water
T_4	Seed coating with 8 g polymer + 40 mL of water
T_5	Seed coating with 8 g polymer + 50 mL of water
T_6	Seed coating with 8 g polymer + 60 mL of water
T_7	Seed coating with 9 g polymer + 40 mL of water
T_8	Seed coating with 9 g polymer + 50 mL of water
T_9	Seed coating with 9 g polymer + 60 mL of water
T_{10}	Seed coating with 10 g polymer + 40 mL of water
T_{11}	Seed coating with 10 g polymer + 50 mL of water
T_{12}	Seed coating with 10 g polymer + 60 mL of water

Vigour index I = Germination (%) × Seedling length (cm) Eq. 2

Vigour index II = Germination (%) × Dry matter production (g/10 seedlings) Eq. 3

Seed biochemical parameters

α Amylase activity (mg maltose min^{-1} g^{-1}) was estimated previously (13). Seed samples (0.5 g) were homogenised in 0.02 M sodium phosphate buffer (pH 6.0) and 20 min centrifugation at 20000 rpm. The extract was incubated with starch solution, the reaction terminated with iodine hydrochloric acid reagent and colour change measured at 620 nm.

Dehydrogenase activity (optical density [OD] g^{-1} mL^{-1}) was estimated as per Kittock and Law (14). Seeds soaked for 3 hr were de coated, incubated in 0.2 % tetrazolium chloride solution for 4 hr in the dark and the formazan extracted overnight in methyl cellosolve. The OD was recorded at 470 nm.

Catalase activity was determined following Aebi (15). Frozen seed samples (20 mg) were homogenised in phosphate ethylenediaminetetraacetic acid (EDTA) extraction buffer and centrifuged at 15000 rpm. The reaction mixture of enzyme extract with hydrogen peroxide was monitored for absorbance decline at 240 nm and activity expressed as µM H_2O_2 decomposed min^{-1} g^{-1}.

Peroxidase activity (U mg^{-1} protein min^{-1}) was measured following the procedure given by of Malik and Singh (16), using pyrogallol and hydrogen peroxide substrate, with the reaction terminated by sulfuric acid and optical density recorded at 420 nm.

Hydropriming (2 hr) was included as a standard reference priming treatment for comparative evaluation of biochemical parameters only (enzyme activity), based on its established use as a conventional priming benchmark in seed physiology literature. Physiological parameters (germination %, root/shoot length, vigour index) were assessed exclusively for the seed-coating treatments and control, as the primary objective of this study was to evaluate polymer-based seed coating; hydropriming was not included in the physiological dataset since it does not represent a coating-based intervention and was outside the comparative scope of that analysis.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) appropriate for a completely randomised design. Germination percentage data were arcsine-transformed before analysis. Treatment means were compared using the critical difference (CD) at the 5 % probability level. Standard error of difference (SEd) was used to quantify the precision of treatment comparisons. AGDATA and AGRES were statistical software used for statistical computations.

Results

Effect on seed physiological characters

All coating treatments significantly improved germination percentage, germination speed, root length, shoot length and vigour index I and II relative to the untreated control, whereas responses in dry matter production varied among treatments. Among the treatments, T_3 (7 g polymer + 60 mL water) was consistently superior, recording the highest speed of germination (9.81 against 6.21 in control) (Fig. 1), the maximum germination (94 % against 70 % in control) (Fig. 2) and the highest root (10.6 cm) and shoot (7.0 cm) length, dry matter production (0.007 g 10 $seedlings^{-1}$) and both vigour indices, recording 34 % improvement in germination percentage and an approximately 97 % improvement in vigour index I over the control. T_8 (92 % germination, vigour index I: 1518) and T_2 (88 % germination, vigour index I: 1478) formed the next best tier, while T_9 recorded the weakest performance among

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the coated treatments, particularly in root length (6.6 cm) and vigour index I (1135), despite an acceptable germination percentage (88 %) (Table 1).

At the lowest polymer dose (7 g), increasing the water volume from 40 to 60 mL produced a steady improvement across every parameter ($T_1 < T_2 < T_3$), whereas at higher polymer doses (8, 9 and 10 g) this water response trend flattened or reversed, with the highest water volume at these doses (T_6, T_9 and T_{12}) failing to match T_3. Vigour index II showed the widest relative spread of all parameters, rising more than 3.1 fold from 0.210 in the control to 0.658 in T_3, reflecting the compounded effect of higher germination and greater dry matter accumulation. Shoot length was comparatively weaker at the 8 g polymer dose (T_4: 5.7 cm; T_6: 5.6 cm) than at other polymer levels, indicating this dose was less favourable specifically for shoot elongation. Overall, treatment ranking based on both vigour indices consistently placed T_3 first, followed by T_7, T_8 and T_2, with T_9 and the untreated control forming the weakest groups (Table 2).

Effect on seed biochemical characters

T_3 recorded the highest α amylase activity (2.789 mg min^{-1} mL^{-1}) and dehydrogenase activity (1.921 OD) among all treatments more than double and two and a half times the control values (1.132 and 0.762), respectively. T_4 (2.152) and T_5 (2.131) formed the next tier for α amylase, while T_2 (1.821) and T_3 (1.921) were the closest competitors for dehydrogenase activity, with both enzymes showing a clear decline at the higher polymer doses of 9 and 10 g (T_7–T_{12}) relative to the 7 and 8 g doses (Table 3). Notably, even the hydropriming treatment, included for comparison, showed only a modest rise over the control (α amylase: 1.351; dehydrogenase: 1.021), well below the levels recorded under T_2, T_3, T_4 and T_5, indicating that polymer coating at the optimum dose was more effective than hydropriming alone in activating these reserve mobilising enzymes. Catalase and peroxidase, in contrast, were not consistently elevated in T_3 relative to other treatments and the treatment effect on both was statistically non-significant (CD, p = 0.05: NS for both) (Table 3).

T_3 recorded comparatively lower catalase and peroxidase values (1.721 and 1.118) than several other treatments and control which received the highest water volume (60 mL) combined with the highest polymer doses (10 g) (Table 3). This divergence between the α amylase/dehydrogenase pattern and the catalase/peroxidase pattern suggests that the two enzyme groups responded differently to the coating treatments, with the former closely tracking seedling vigour and the latter showing no clear dose dependent trend across the polymer water combinations tested.

Discussion

Among the tested polymer-to-water combinations, T_3 (7 g polymer + 60 mL water) produced the strongest overall physiological response. The superior performance of this formulation may be related to the coating characteristics generated by its polymer concentration and dilution, although coating thickness and seed hydration were not directly measured in the present study. Hydrophilic polymer films are known to form a thin mucilage layer around the seed on contact with free water and this layer has been shown to facilitate faster and more controlled imbibition, manifesting as a significantly reduced mean germination time in coated tomato seed compared with uncoated seed (17). A thin, well diluted film at the low polymer load used in T_3 likely reproduces this effect, permitting rapid and uniform hydration, whereas thicker films formed at higher polymer concentrations may restrict water and gas exchange around the seed. Coating thickness is, in fact, a recognised design parameter in seed coating technology, with film permeability shown to be tunable through the quantity and composition of polymer applied rather than being a fixed property of the polymer itself (18).

Seed characteristics and external coating properties can influence the rate and extent of water uptake before germination (19). Differences in coating formulation may therefore contribute to the contrasting germination responses observed among treatments (19). The lower performance of several 9 and 10 g polymer treatments, particularly at the higher water volumes, suggests that increasing polymer quantity did not consistently improve seed performance. Differences in coating properties and seed hydration may contribute to this response, although these factors were not directly measured. This pattern is consistent with observations in other small-seeded vegetable crops, where coating thickness has been shown to be a more critical determinant of germination performance than in larger-seeded species. In lettuce (*Lactuca sativa* L.), a small, elongated seed comparable in scale to palak, commercial clay-based coating delayed germination and reduced the maximum germination temperature relative to uncoated seed, an effect attributed to the added coating mass restricting water uptake and gas exchange during imbibition (20). Seed coating with indole-3-acetic acid (IAA) has increased the physiological seed parameters in soybean (21). The gains recorded here for T_3 in speed of germination, germination (Fig. 3), root and shoot length and vigour indices are further consistent with the broader body of evidence on polymer and nutrient enriched seed coatings, where such coatings have been shown to stimulate α amylase and protease activity indispensable for nutrient mobilisation, translating into faster and more uniform seedling establishment (22).

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Table 1. Effect of seed coating using TNAU Vidhai Amirtham on seed physiological characters Palak cv. All Green seeds

Treatments	Speed of germination				Germination (%)				Root length (cm)				Shoot length (cm)			
Water volume Polymer weight	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**
Control	6.21	6.21	6.21	6.21	70 (56.79)	70 (56.79)	70 (56.79)	70 (56.79)	7.10	7.10	7.10	7.1	4.9	4.9	4.9	4.9
7 g	8.15	8.92	9.81	8.96	84 (66.42)	88 (69.73)	94 (75.82)	89 (70.63)	10.0	10.1	10.6	10.2	6.6	6.7	7.0	6.8
8 g	8.98	8.92	8.99	8.96	88 (69.73)	90 (71.52)	89 (70.63)	89 (70.63)	10.4	10.0	9.7	10.0	5.7	5.9	5.6	5.7
9 g	9.31	9.41	8.87	9.20	90 (71.52)	92 (73.53)	88 (69.73)	90 (71.52)	10.1	9.6	6.6	8.8	6.8	6.9	6.3	6.7
10 g	8.21	8.53	7.62	8.12	80 (63.43)	84 (66.42)	82 (64.90)	82 (64.90)	9.9	8.9	8.3	9.0	6.2	6.2	6.3	6.2
Mean	8.17	8.40	8.30	8.29	82 (64.90)	85 (67.12)	85 (67.12)	84 (66.42)	9.5	9.1	8.5	9.0	6.0	6.1	6.0	6.1
SEd	0.112	0.087	0.195		0.919	0.712	1.592		0.119	0.092	0.206		0.081	0.063	0.141	
CD (p = 0.05)	0.230	0.178	0.399		1.878	1.454	3.252		0.243	0.188	0.421		0.167	0.129	0.289	

Figures in parentheses indicates arcsine values.

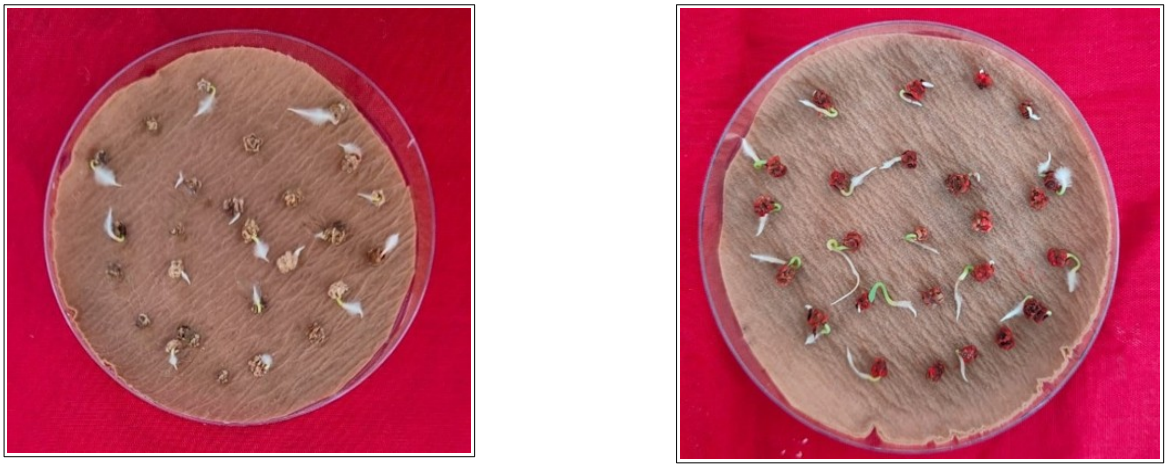
Table 2. Effect of seed coating with TNAU Vidhai Amirtham on dry matter production and seedling vigour of palak cv. All Green

Treatments	Dry matter production (g/ 10 seedlings)				Vigour index I				Vigour index II			
Water volume Polymer weight	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**
Control	0.0032	0.0032	0.0032	0.0032	840	840	840	840	0.210	0.210	0.210	0.210
7 g	0.0035	0.0042	0.0073	0.0050	1394	1478	1654	1509	0.252	0.352	0.658	0.421
8 g	0.0070	0.0051	0.0062	0.0061	1417	1431	1362	1403	0.616	0.450	0.534	0.533
9 g	0.0052	0.0063	0.0070	0.0062	1521	1518	1135	1391	0.450	0.552	0.616	0.539
10 g	0.0063	0.0042	0.0045	0.0050	1288	1268	1197	1251	0.480	0.336	0.328	0.381
Mean	0.0050	0.0046	0.0056	0.0051	1292	1307	1238	1279	0.402	0.380	0.469	0.417
SEd	0.00006	0.00005	0.00011		13.58	10.52	23.52		0.005	0.004	0.009	
CD (p = 0.05)	0.00013	0.00010	0.00022		27.74	21.49	48.01		0.010	0.008	0.019	

Table 3. Effect of seed coating using TNAU Vidhai Amirtham on seed biochemical characters of palak cv. All Green seeds

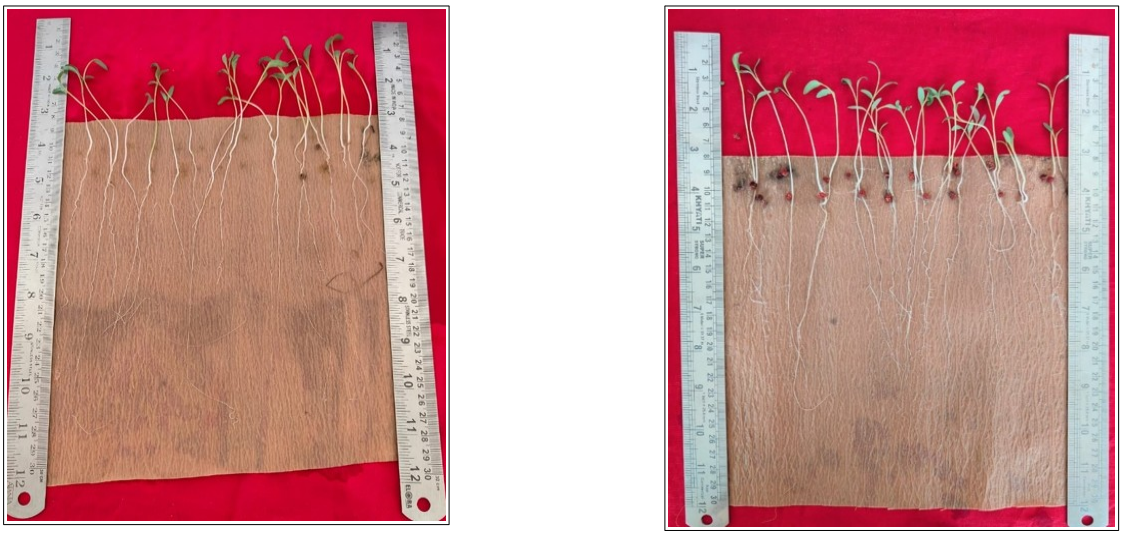
Treatments	α Amylase (mg min^{-1} mL^{-1})				Dehydrogenase (OD)				Catalase (µmol H_2O_2 $min^{-1}g^{-1}$)				Peroxidase (mg^{-1} protein min^{-1})			
Water volume Polymer weight	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**	**40 mL**	**50 mL**	**60 mL**	**Mean**
Control	1.132	1.132	1.132	1.132	0.762	0.762	0.762	0.762	1.732	1.732	1.732	1.732	1.098	1.098	1.098	1.098
Hydropriming - 2 hr	1.351	1.351	1.351	1.351	1.021	1.021	1.021	1.021	1.801	1.801	1.801	1.801	1.121	1.121	1.121	1.121
7 g	1.422	1.912	2.789	2.041	1.775	1.821	1.921	1.839	1.791	1.783	1.721	1.765	1.121	1.123	1.118	1.121
8 g	2.152	2.131	2.003	2.095	1.812	1.755	1.621	1.729	1.721	1.698	1.761	1.727	1.112	1.123	1.112	1.116
9 g	1.512	1.675	1.912	1.700	1.521	1.632	1.521	1.558	1.762	1.712	1.761	1.745	1.100	1.131	1.121	1.117
10 g	1.875	1.722	1.612	1.664	1.412	1.612	1.721	1.382	1.768	1.721	1.712	1.754	1.125	1.131	1.112	1.115
Mean	1.574	1.654	1.800	1.664	1.384	1.434	1.428	1.382	1.763	1.741	1.748	1.754	1.113	1.121	1.114	1.115
SEd	0.020	0.014	0.036		0.017	0.012	0.029		0.017	0.012	0.030		0.014	0.010	0.025	
CD (p = 0.05)	0.042	0.029	0.073		0.035	0.024	0.060		NS	NS	NS		NS	NS	NS	

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Control on 2nd day | 7 g of polymer + 60 mL water on 2nd day

Fig. 1. Effect of seed coating on speed of germination of palak cv. All Green seeds.



Control | 7 g of polymer + 60 mL water

Fig. 2. Effect of seed coating on seedling growth of palak cv. All Green seeds.

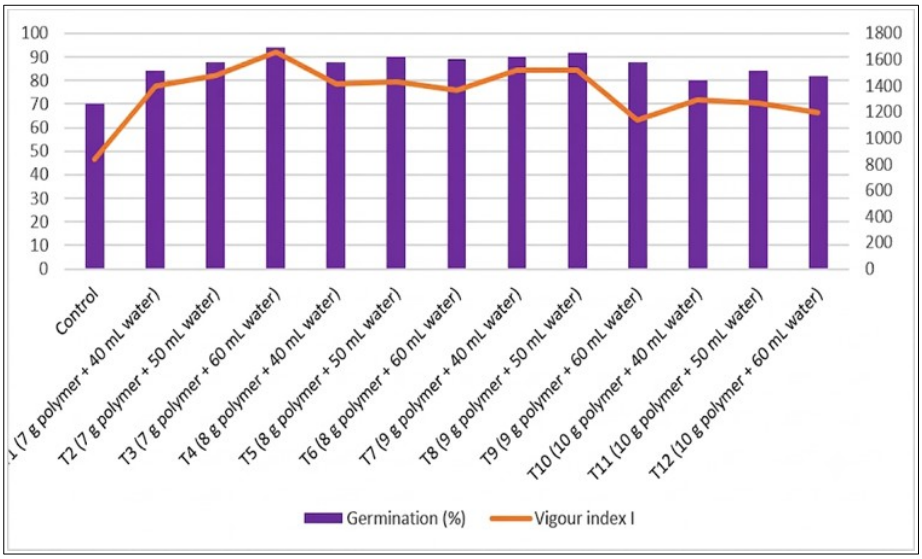


Fig. 3. Effect of seed coating on germination (%) and vigour index I of palak cv. All Green seeds.

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The biochemical results reinforce this physiological picture and point toward a plausible underlying mechanism. α Amylase governs the hydrolysis of stored starch into soluble sugars that fuel embryo growth during early germination and its marked elevation under T_3 (Table 3) is consistent with reports that coating seeds with nutrient formulations enhances germination and seedling growth while promoting dehydrogenase activity during germination in vegetable crops (23), as well as findings that nanoparticle film coatings on legume seed significantly increased seedling emergence, vigour and both dehydrogenase and amylase activities compared with untreated seed (24). Dehydrogenase activity followed a pattern like that of α-amylase, with T_3 showing the highest activity. The concurrent increase in these biochemical markers and seedling vigour supports an association between enhanced metabolic activity and improved germination performance under T_3.

Catalase and peroxidase activities showed no significant treatment effects in the present study. Although T_3 exhibited relatively low values for these enzymes, the absence of significant treatment differences does not allow a firm conclusion regarding oxidative stress or antioxidant responses. This interpretation is consistent with evidence that nutrient-enriched seed coatings elevate antioxidant enzyme activities, including catalase and peroxidase, specifically to maintain membrane stability and vigour under conditions of oxidative or hydration stress (24), implying that when such stress is minimal, as may be the case under an optimally diluted coating like T_3, the compensatory rise in these enzymes is correspondingly smaller. However, since the treatment effect on catalase and peroxidase was statistically non-significant (CD, p = 0.05: NS), this interpretation should be treated as indicative rather than conclusive.

Taken together, the physiological and biochemical results identify T_3, comprising 7 g polymer diluted in 60 mL water, as the best-performing formulation among those tested for improving palak seed germination and early seedling vigour. The underlying contribution of coating thickness and seed hydration remains to be established through direct measurements. TNAU Vidhai Amirtham can be positioned within the broader landscape of seed coating polymers to contextualise the present findings. Chitosan, among the most studied natural seed coating polymers, improves germination partly through direct cationic bioactivity at the plant cell membrane, beyond its role as a film former (25). Cellulose derivatives such as carboxymethyl cellulose (CMC), by contrast, act mainly as inert hydrophilic film formers; in wheat, moderate CMC levels improved germination and vigour by 5–10 % over untreated seed, while higher concentrations reduced growth due to excessive film rigidity (26), a dose-dependent decline mirroring the poorer performance of the higher polymer dose treatments in the present study. Synthetic binders such as polyvinyl alcohol (PVA) and polyethylene glycol (PEG) are also widely used for dust reduction and germination enhancement but lack the biodegradability and bioactivity of natural polymers like chitosan (27). Functionally, Vidhai Amirtham appears closer to the cellulose/starch-based film-forming class than to bioactive polymers such as chitosan, deriving its benefit mainly from controlled hydration and nutrient delivery rather than membrane-level bioactivity consistent with the dose-sensitive, thickness-dependent response observed here (26).

Conclusion

This study demonstrates that the efficacy of TNAU Vidhai Amirtham, a seed coating previously evaluated in cereal crops, has potential for application to a leafy vegetable through appropriate dose standardisation. Among the combinations evaluated, 7 g polymer diluted in 60 mL water emerged as the optimum formulation for palak cv. All Green. The consistent alignment between physiological performance and reserve mobilising enzyme activity at this combination indicates that coating efficacy in this system is governed primarily by the ratio between polymer and water rather than by polymer quantity alone, likely through its influence on coating film permeability and imbibition rate. The comparatively stable antioxidant enzyme response across treatments points toward minimal oxidative stress under the optimum formulation, although this remains a hypothesis warranting confirmation through more targeted redox assays. The dose-optimisation approach used in this study may provide a basis for further evaluation of seed-coating formulations in other small-seeded vegetable crops. The approach provides a basis for evaluating polymer-to-water combinations in other vegetable seed systems, although its applicability to other crops and cultivars requires independent validation. Field level validation of the identified formulation is recommended as the logical next step, positioning TNAU Vidhai Amirtham as a potential low cost, chemical free seed enhancement technology goals for vegetable production systems.

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Authors' contributions

RG was responsible for conceptualisation, investigation, methodology and writing - original draft. KM, PSM and ME contributed to conceptualisation and methodology. KM and ME contributed to supervision, while KM, PSM, TE, CT, VSM and ME contributed to review and editing. PSM and CT contributed to resources. TE contributed to methodology and supervision. All authors have read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT solely to improve the language and grammar of the manuscript and Claude (Anthropic) was used for language polishing of the Discussion section, literature summarisation, formatting assistance. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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