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Plasma seed technology: Revolutionizing seed germination and vigour for sustainable crop improvement

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Abstract

Plasma Seed Technology is a novel, eco-friendly pre-sowing method that employs non-thermal plasma to improve seed performance without relying on chemicals. This research intended to assess the effect of plasma exposure time and seed positioning (with or without rotation) on germination and initial seedling strength in tomato (*Solanum lycopersicum*), brinjal (*Solanum melongena*), and chilli (*Capsicum annuum*). Seeds underwent cold plasma treatment for different exposure durations (4 to 32 seconds), with and without rotation, alongside an untreated control. Fourteen plasma treatments were assessed, and the impacts on germination rate, average germination duration, seedling height, and vigour index were noted under regulated conditions. Of all treatments, 16 seconds of plasma exposure without flipping consistently surpassed others in all three crops. This therapy greatly enhanced germination rates and seedling strength in comparison to the control and other plasma exposure times. The enhancement is linked to the improved interaction of Reactive Oxygen and Nitrogen Species (RONS) generated by plasma with the seed surface, which increased seed coat permeability, activated enzymes, and achieved microbial decontamination, while avoiding oxidative harm that could arise from prolonged exposures. The results indicate that a 16-second plasma treatment without flipping is an effective and optimal method for improving seed quality and initial seedling development in solanaceous vegetables. This method has significant potential to be incorporated into commercial seed treatment programs as an environmentally friendly substitute for chemical priming techniques.

Keywords: Plasma seed technology, non-thermal plasma, seed germination, seedling vigour, solanaceous vegetables, tomato, brinjal, chilli

Introduction

The increasing need for sustainable agricultural products and vegetable raw materials has pressured researchers to create sustainable methods for improving crop yields (Randeniya & de Groot, 2015) ^[18]. The germination and strength of seeds are essential for establishing crops; however, issues like poor germination, late emergence, and frail seedlings are frequently observed in horticultural crops such as brinjal, tomato, and chilli (Filatova *et al.*, 2011; Misra *et al.*, 2014) ^[7, 16].

Chilli (*Capsicum annuum* L.), appreciated as a seasoning and flavouring, frequently exhibits delayed and inconsistent germination, particularly under abiotic stress (Sivachandiran & Khacef, 2017) ^[20]. Tomato (*Solanum lycopersicum* L.), a crucial vegetable worldwide and rich in vitamins A and C, experiences seed dormancy and low germination rates despite being stored (Groot *et al.*, 2012) ^[9]. Brinjal (*Solanum melongena* L.), another key crop, faces challenges due to irregular germination and pathogens carried by seeds (Khan *et al.*, 2016) ^[14]. Due to the fact that traditional seed priming techniques use chemicals that can create residues and negatively impact the environment (Varier *et al.*, 2010) ^[23], sustainable alternatives are required.

Plasma Seed Technology (PST), which utilizes non-thermal plasma made up of Reactive Oxygen and Nitrogen Species, ions, and UV photons (Fridman, 2008) ^[8], provides an eco-friendly, non-chemical alternative. It improves seed water affinity, eliminates dormancy, minimizes pathogens, and encourages processes related to germination (Dobrin *et al.*, 2015) ^[6]. The effectiveness of treatment relies on the duration and orientation of seeds during exposure (Sera *et al.*, 2008) ^[19]. Although successful for cereals and legumes, standardized protocols for solanaceous vegetables remain sparse. The goals of this research are to analyse

the impact of plasma exposure on seed germination, examine its effects on seedling vitality, and identify the ideal exposure time and seed positioning that enhance seed performance. Additionally, the research seeks to investigate Plasma Seed Technology (PST) as a sustainable, environmentally friendly, and non-chemical approach for improving seed quality and crop establishment in solanaceous vegetables.

Materials and Methods

Location of the Experiment and Temperature Details

The study was performed at PunjaithuraiPalayam, Erode District, Tamil Nadu, under meticulously controlled laboratory settings to guarantee accuracy and consistency. A programmable growth chamber was utilized to sustain an ideal temperature of $25 \pm 2^\circ\text{C}$ and a relative humidity of 60-70%, establishing a supportive environment for the germination of solanaceous plants like tomato, brinjal, and chilli. A 12-hour light/12-hour dark cycle was implemented with cool white fluorescent lamps at an intensity of 3000-3500 lux to mimic natural day-night rhythms and promote photomorphogenesis. Seeds were germinated using the roll towel technique on damp germination paper, ensuring consistent moisture throughout all treatments. Consistent observation maintained slight variations in environmental factors, thus removing external effects. These uniform conditions facilitated an accurate evaluation of germination behaviour, seedling strength, and initial growth performance of plasma-treated seeds relative to untreated controls

Experimental Design

The experiment was arranged in a Completely Randomized Design (CRD) featuring three replications for each of the chosen solanaceous crop's tomato (cv. Pusa Ruby), aubergine (cv. Arka Nidhi) and chili (cv. Kashi Anmol). A total of thirteen treatments were applied, including an untreated control and plasma exposures varying from 4 to 32 seconds, each evaluated with and without flipping to consider seed orientation impacts. For every replication, 25 seeds were utilized and sprouted under regulated laboratory conditions, adhering to the roll towel technique according to ISTA (2015) standards. Data were collected on germination rate, germination speed, root length, shoot length, seedling vigour index, and additional physiological characteristics at set intervals. Statistical analysis utilized ANOVA as outlined by Gomez and Gomez (1984), and treatment means were compared with the Least Significant Difference (LSD) test at the 5% significance level to determine significant differences among treatments. The plasma exposure was conducted with a Dielectric Barrier Discharge (DBD) system functioning at atmospheric pressure, frequently utilized in seed improvement studies. This experimental setup enabled a systematic assessment of plasma treatment times and angles, thereby determining their impact on seed germination, seedling development, and vigour

Seed Material

Certified seeds of three important solanaceous vegetable species - tomato (*Solanum lycopersicum* cv. Pusa Ruby), brinjal (*Solanum melongena* cv. Arka Nidhi), and Chilli (*Capsicum annuum* cv. Kashi Anmol) were employed in this research. These cultivars were selected for their wide adaptability, genetic purity, and economic importance in Indian horticulture, and were obtained from the Department

of Vegetable Crops, Tamil Nadu Agricultural University (TNAU), Coimbatore.

Seeds were selected for experimental purposes only if they displayed no indications of mechanical damage, insect infestations, fungal contamination, or visible deformities. Seeds were kept in ambient room conditions (protected from excessive heat, humidity, and direct sunlight) until the treatment and germination tests, following best practices to maintain physiological integrity and viability (McDonald, 1999).

Plasma Treatment Setup

In this study, a non-thermal cold plasma system combined with a Dielectric Barrier Discharge (DBD) plasma generator was utilized for modifying seed surfaces. DBD plasma systems are recognized for producing stable, non-thermal plasmas at atmospheric pressure, which makes them suitable for biological uses like seed treatment. The plasma was produced using ambient atmospheric air as the working gas, removing the necessity for expensive and dangerous carrier gases such as argon or helium, thereby making the technology both environmentally sustainable and economically feasible. The system functioned at a high-voltage level of 20 to 25 kilovolts (kV) with a frequency of 50 Hz, adequate to trigger and maintain dielectric barrier discharges between the electrodes. The discharge took place between a high-voltage electrode and a grounded electrode, separated by a dielectric barrier that inhibited spark formation and guaranteed even plasma distribution over the seed surface. The treatment chamber was engineered to hold several seeds in a single-layer configuration, guaranteeing uniform exposure to reactive plasma components, including Reactive Oxygen and Nitrogen Species (RONS), UV radiation, and charged particles. These active plasma elements are recognized for changing the physicochemical characteristics of the seed coat improving water absorption, reducing microbial load, and stimulating metabolic processes essential for initial germination. The complete plasma treatment process was carried out at normal room temperature, maintaining seed viability while promoting advantageous biochemical and physiological alterations. Operational safety protocols, such as grounding, insulation, and shielding, were diligently adhered to throughout the plasma application procedure.

Table 1: Treatment Details

S.NO.	Treatment	S.NO.	Treatment
T ₁	Control	T10	20 Seconds with flipping
T ₂	4 Seconds with flipping	T11	20 Seconds without flipping
T ₃	4 Seconds without flipping	T12	24 Seconds with flipping
T ₄	8 Seconds with flipping	T13	24 Seconds without flipping
T ₅	8 Seconds without flipping	T14	28 Seconds with flipping
T ₆	12 Seconds with flipping	T15	28 Seconds without flipping
T ₇	12 Seconds without flipping	T16	32 Seconds with flipping
T ₈	16 Seconds with flipping	T17	32 Seconds without flipping
T ₉	16 Seconds without flipping		

Flipping refers to manually turning the seeds at the halfway point during treatment to ensure both sides are equally exposed to plasma.

Collection of Seeds

The seeds utilized in this study were gathered from verified and recognized sources to guarantee genetic integrity and consistency. Seeds of tomato (*Solanum lycopersicum*) cultivar. Pusa Ruby, brinjal (*Solanum melongena*) variety.

Arka Nidhi and chilli (*Capsicum annuum*) cultivar. Kashi Anmol was obtained from the Department of Vegetable Crops at Tamil Nadu Agricultural University (TNAU) in Coimbatore. These varieties were chosen for their consistent performance, favour among growers, and sensitivity to seed improvement methods. Once obtained, the seed lots underwent a detailed examination for physical purity, consistency in size and colour, and lack of noticeable damage or microbial contamination. Only seeds that fulfilled the minimum seed certification criteria (according to the Indian Minimum Seed Certification Standards, 2013) were utilized for the research. The seeds were preserved in tidy, dry, and sealed containers at normal room temperature (25-28°C) until needed, ensuring their physiological integrity and viability were kept intact before plasma treatment.

Results and Discussion

Table 2: Effect of plasma seed treatment on germination percentage, root length, shoot length, and vigour index in tomato:

Treatment	Germination %	Root Length (cm)	Shoot Length (cm)	Vigour Index
T ₁	78.0	4.5	8.77	1035.06
T ₂	74.0	5.75	8.5	1054.5
T ₃	84.0	4.2	7.9	1016.4
T ₄	58.0	4.9	9.1	812.0
T ₅	84.0	5.6	8.6	1192.8
T ₆	72.0	4.32	7.65	883.44
T ₇	78.0	4.4	8.97	1042.86
T ₈	74.0	4.77	8.27	964.96
T ₉	92.0	5.9	8.7	1343.2
T ₁₀	80.0	4.72	8.7	1073.6
T ₁₁	85.5	4.75	8.7	1149.97
T ₁₂	62.0	4.11	9.02	813.75
T ₁₃	76.0	4.62	9.91	1104.66
T ₁₄	62.5	4.25	8.94	824.07
T ₁₅	58.0	3.75	8.48	709.63
T ₁₆	72.0	4.98	8.7	984.96
T ₁₇	80.0	4.8	8.47	1061.6
Mean	74.71	4.72	8.67	1003.97
SD	9.85	0.58	0.5	158.9
CV	13.18	12.36	5.72	15.83

The cold-plasma treatments produced clear and consistent differences in tomato seed performance. Treatment 16 seconds without flipping gave the best overall outcome, producing the highest vigour index (1343.20), high germination (92.0%), and strong root development (5.90 cm), while shoot length remained comparable to the better treatments (8.70 cm). Other treatments that performed well were 8 seconds without flipping (germination 84.0%, root 5.60 cm, vigour 1192.80) and 20 seconds without flipping (germination 85.5%, vigour 1149.97). Some treatments boosted one component but not overall vigour—for example, 24 seconds without flipping gave the highest shoot length (9.91 cm) but only moderate germination (76.0%) and vigour (1104.66). The poorest performances were observed for 28 seconds without flipping (germination 58.0%, root 3.75 cm, vigour 709.63) and 8 seconds with flipping (germination 58.0%, vigour 812.00), indicating that either too long an exposure or certain short-exposure/flipping combinations can be detrimental.

Germination Procedure (Roll Towel Method)

Germination assessments were performed utilizing the Roll Towel Method, following the standards set by the International Seed Testing Association (ISTA, 2023). This approach was chosen due to its dependability in offering a consistent and regulated setting for assessing seed germination and initial seedling development. For every treatment, 100 seeds were tested per crop per replication (amounting to 300 seeds per treatment per crop in total). The roll towel technique maintained uniform conditions throughout treatments and facilitated precise measurement of seedling root and shoot lengths, essential for computing the Seedling Vigour Index and evaluating plasma exposure effects

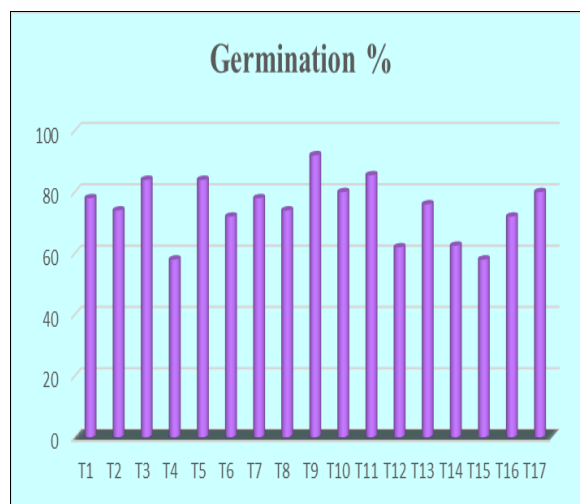
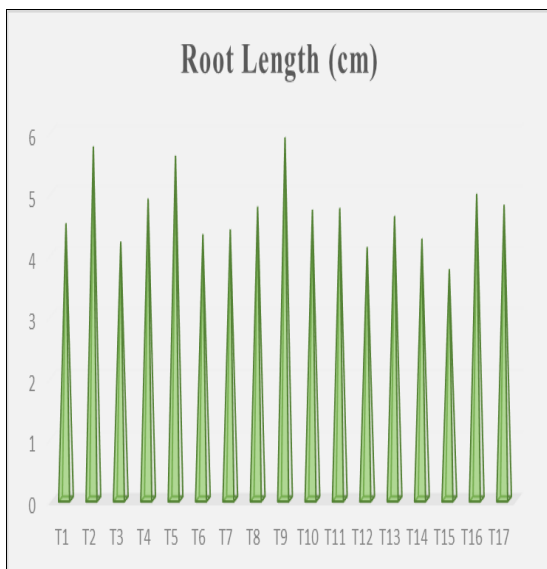
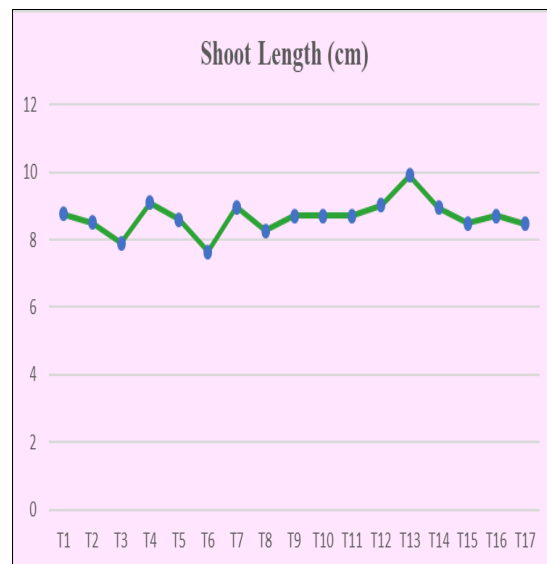
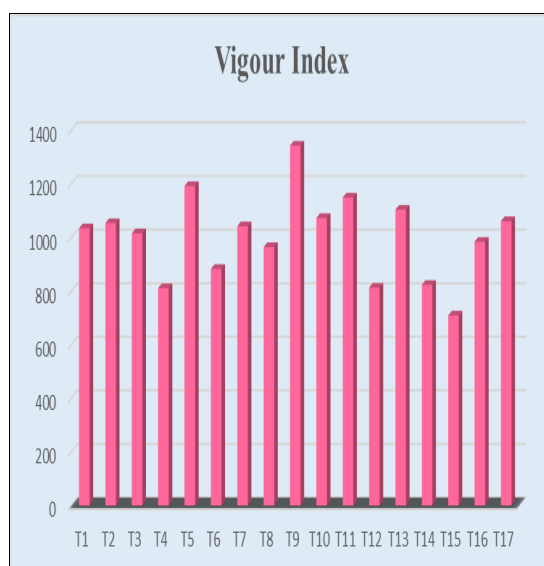


Fig 1 (a): Germination percentage of tomato

**Fig 1(b):** Root length of tomato (cm)**Fig 1(c):** Shoot length of Tomato (cm)**Fig 1(d):** Vigour index of Tomato**Table 2:** Effect of plasma seed treatment on germination percentage, root length, shoot length, and vigour index in brinjal:

Treatment	Germination %	Root Length (cm)	Shoot Length (cm)	Vigour Index
T ₁	94	5.4	5.52	1026.48
T ₂	96	4.81	5.96	1033.92
T ₃	96	4.44	6.34	1034.88
T ₄	94	4.825	6.48	1062.67
T ₅	92	5.09	5.57	980.72
T ₆	92	4.95	5.6	970.6
T ₇	96	5.52	5.72	1079.04
T ₈	96	7.7	5.36	1253.76
T ₉	86	6.7	5.6	1057.8
T ₁₀	96	6.72	5.57	1179.84
T ₁₁	96	6.25	5.95	1049.2
T ₁₂	96	6.05	5.56	1114.56
T ₁₃	88	5.4	5.12	925.76
T ₁₄	94	5.23	5.71	1028.36
T ₁₅	86	4.32	5.61	853.98
T ₁₆	80	5.795	5.74	922.8
T ₁₇	94	5.315	5.53	1019.43
Mean	92.47	5.56	5.70	1034.93
SD	4.72	0.89	0.33	94.65
CV	5.10	16.03	5.79	9.15

The plasma treatments produced clear differences across the four measured traits. The best overall performance in this dataset was observed with 16 seconds with flipping, which recorded the largest root length (7.70 cm) and the highest vigour index (1253.76) while maintaining a high germination (96%). Other strong-performing treatments were 20 seconds with flipping (vigour 1179.84, germination 96%), 24 seconds with flipping (vigour 1114.56, germination 96%) and 12 seconds without flipping (vigour 1079.04, germination 96%). Germination percentage was highest (96%) in several treatments (4 s with flip, 4 s without flip, 12 s without flip, 16 s with flip, 20 s with flip/no-flip, 24 s with flip, 32 s without flip), showing that many plasma regimes produced high emergence. The poorest performance was recorded for 28 seconds without flipping (lowest vigour index 853.98 and reduced root length 4.32 cm). Other lower-performing treatments included 32 seconds with flipping (vigour 922.80) and 24 seconds without flipping (vigour 925.76).

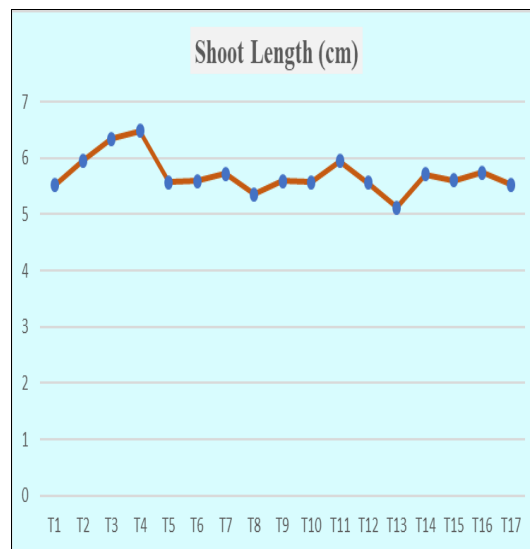


Fig 2(c): Shoot length of Brinjal (cm)

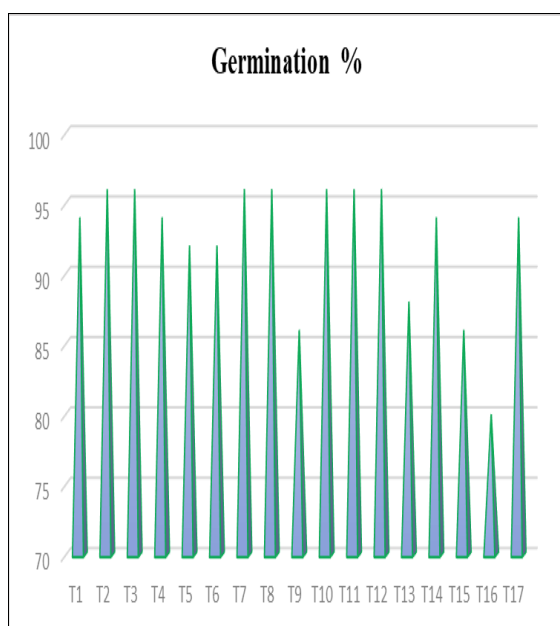


Fig 2 (a): Germination percentage of Brinjal

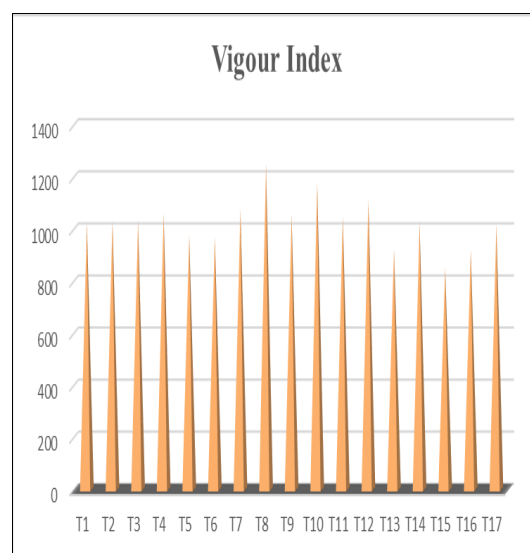


Fig 2(d): Vigour index of Brinjal

Table 3: Effect of plasma seed treatment on germination percentage, root length, shoot length, and vigour index in chilli

Treatment	Germination %	Root Length (cm)	Shoot Length (cm)	Vigour Index
T ₁	92	6.845	5.46	1132.06
T ₂	96	4.81	5.96	1033.92
T ₃	96	4.44	6.34	1034.88
T ₄	84	7.61	5.525	1103.34
T ₅	82	11.55	5.65	1410.4
T ₆	92	4.95	5.6	970.6
T ₇	96	5.52	5.72	1079.04
T ₈	88	7.675	5.475	1157.2
T ₉	96	10.175	5.425	1497.6
T ₁₀	96	6.72	5.57	1179.84
T ₁₁	96	6.25	5.95	1049.2
T ₁₂	94	7.575	5.89	1265.71
T ₁₃	92	7.675	5.3	1193.7
T ₁₄	96	9.815	5.705	1489.92
T ₁₅	94	8.855	5.13	1314.59
T ₁₆	94	7.67	5.725	1259.13
T ₁₇	88	8.825	4.77	1196.36
Mean	92.47	7.47	5.60	1198.09
SD	4.45	1.97	0.35	157.89
CV	4.81	26.41	6.31	13.18

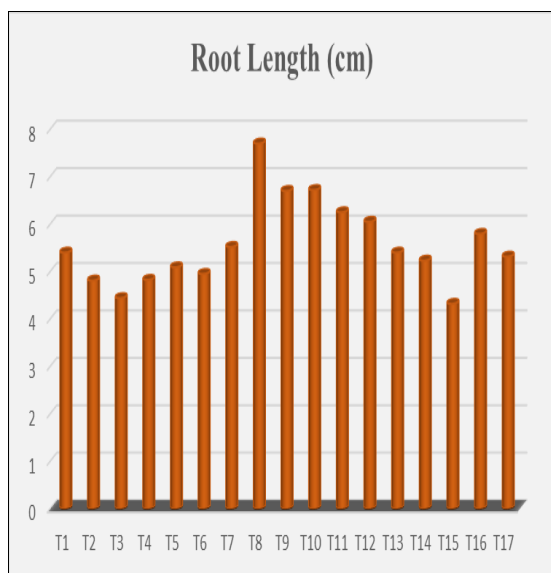


Fig 2(b): Root length of Brinjal (cm)

The plasma treatments produced clear differences in germination and early seedling growth. Several treatments achieved the top germination values (96%): 4 s with flipping, 4 s without flipping, 12 s without flipping, 16 s without flipping, 20 s with flipping, 20 s without flipping, and 28 s with flipping. The largest root length was observed under 8 seconds without flipping (11.55 cm), while the maximum shoot length occurred with 4 seconds without flipping (6.34 cm). Crucially, the highest vigour index — the composite indicator of emergence $\times$ seedling size — was recorded for 16 seconds without flipping (1497.6), followed closely by 28 seconds with flipping (1489.92) and 8 seconds without flipping (1410.4). The weakest vigour was recorded for 12 seconds with flipping (970.6). Overall, intermediate-to-moderately long exposures without flipping (notably 16 s no flip, and 8 s no flip for root growth) produced the strongest seedlings, whereas some other combinations (e.g., certain flipped or very short exposures) performed less well.

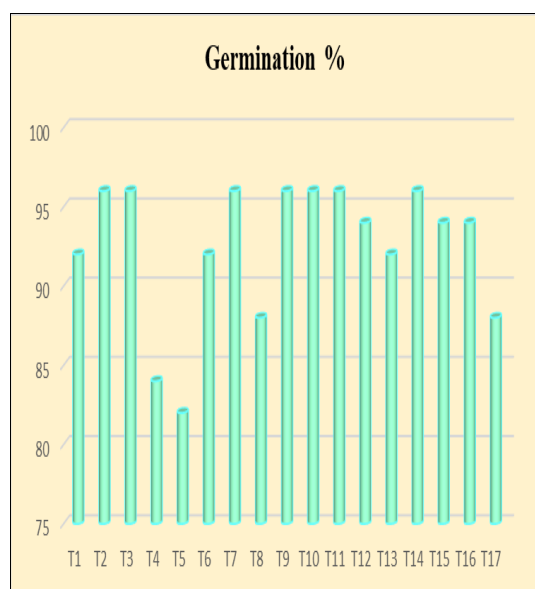


Fig 3(a): Germination Percentage of Chilli

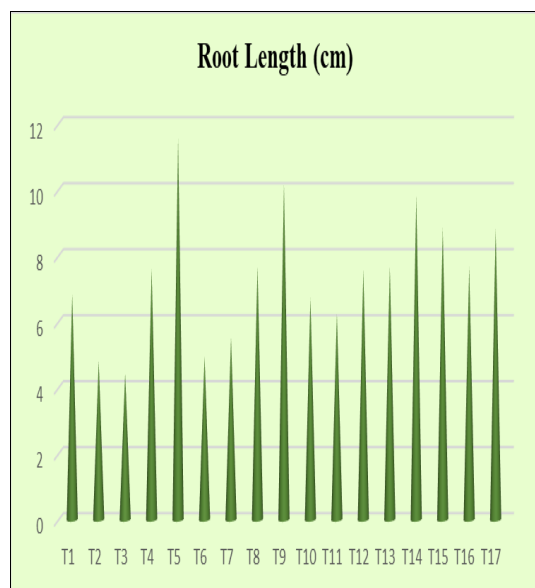


Fig 3(b): Root length of Chilli (cm)

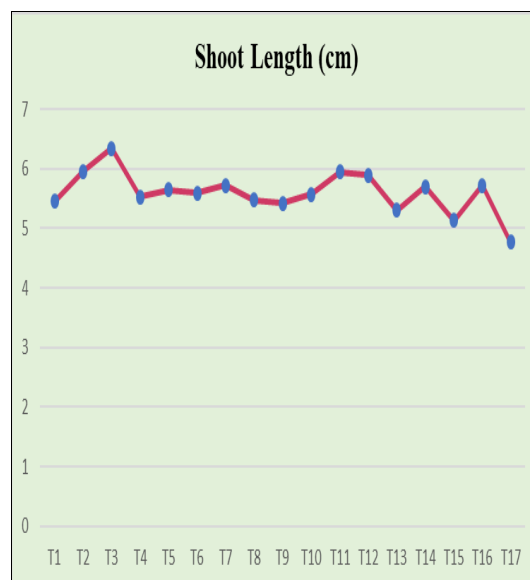


Fig 3(c): Shoot Length of Chilli (cm)

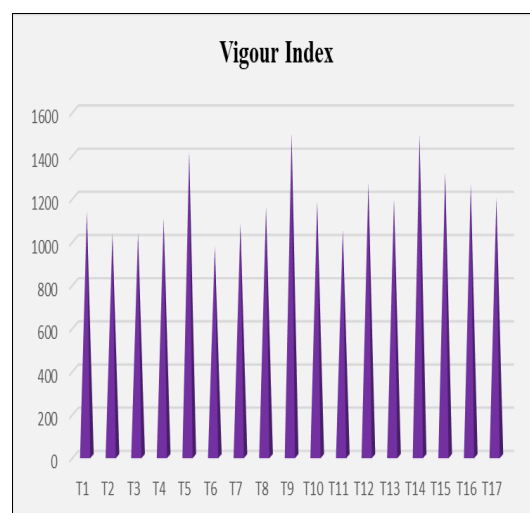


Fig 3(d): Vigour index of Chilli

Conclusion

The present study demonstrates that Plasma Seed Technology (PST) is a promising, eco-friendly, and non-chemical approach to enhancing seed germination and seedling vigour in solanaceous vegetables. Cold plasma treatment significantly influenced seed performance, with clear variations across exposure durations and seed orientations. Among the treatments, 16 seconds of exposure without flipping consistently produced the highest germination percentage, root development, and vigour index in tomato, brinjal, and chilli, highlighting it as the most effective protocol. The improvement can be attributed to plasma-induced modifications in seed coat permeability, enhanced water uptake, microbial decontamination, and activation of enzymatic and physiological processes. Unlike conventional priming methods that rely on chemicals, PST provides a safe and sustainable alternative aligned with the goals of organic and ecological farming. These findings establish plasma treatment as a valuable seed enhancement tool with strong potential for large-scale adoption in horticultural seed industries to ensure better crop establishment and productivity.

Discussion

This study showed that cold plasma treatment significantly improved seed germination and vigour in tomato, brinjal, and chilli, though the effects varied with exposure time and orientation. Tomato and chilli responded best to 16 seconds without flipping, which gave the highest germination and vigour indices, while brinjal performed better at 16 seconds with flipping, likely due to its thicker seed coat. Short exposures provided moderate benefits, whereas longer durations (28-32 seconds) reduced performance, indicating oxidative stress. Overall, plasma treatment at optimal exposure enhances seed coat permeability, water uptake, and root development, making it a sustainable alternative to chemical priming for solanaceous crops.

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