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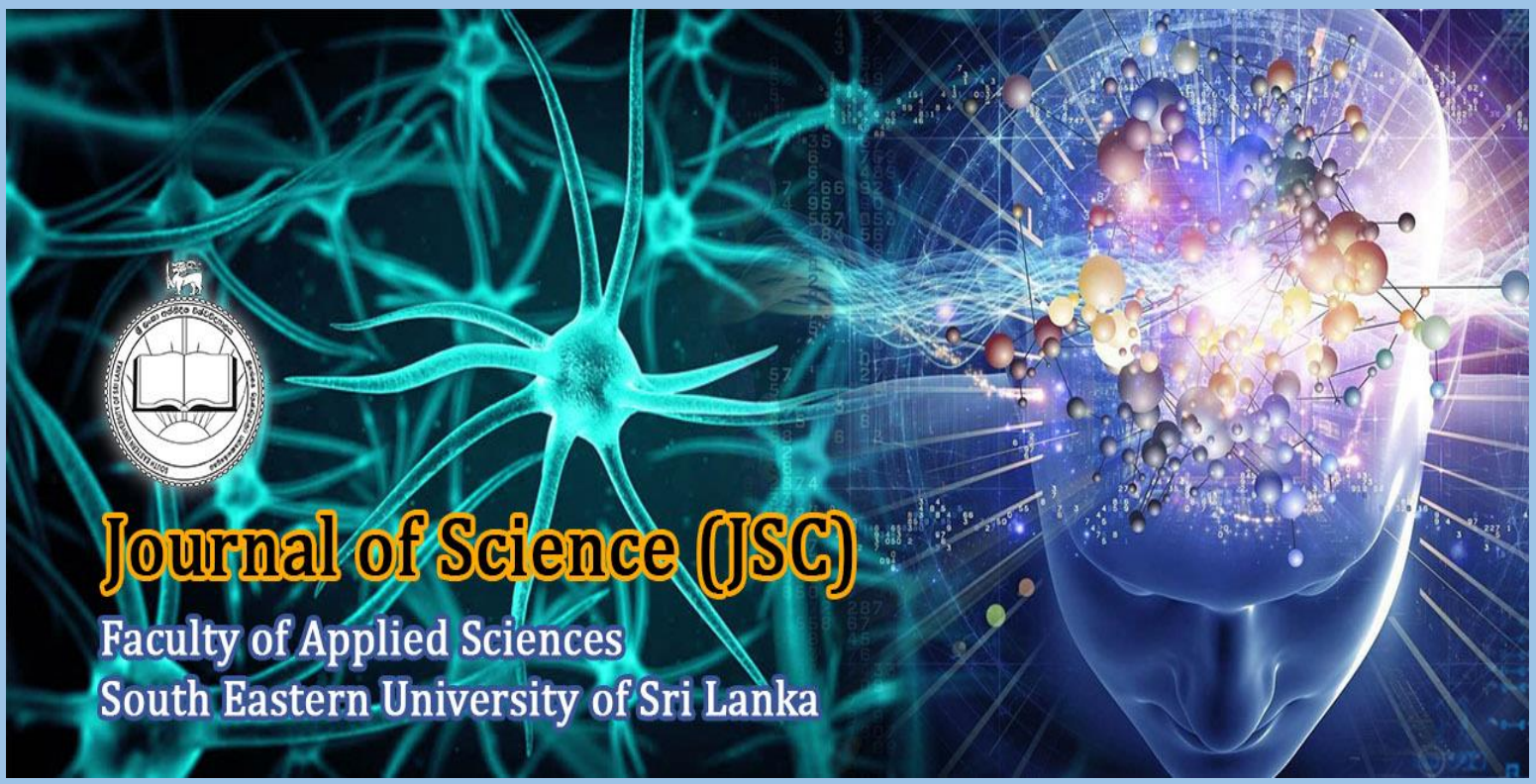

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Influence of priming agents on Okra seed germination and growth under salinity stress

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Abstract

Salinity is a major abiotic factor which severely limits okra seed germination and early seedling growth. Therefore, this study examines the impact of different priming agents such as carrot root extract, neem leaf extract, garlic clove extract, and $MgSO_4$ on modulating okra (MI-5 Variety) seed germination and plant growth under salinity stress conditions. Firstly, a laboratory experiment was designed to identify a suitable concentration from each of the selected four priming agents based on their reported ability to enhance germination of the okra seeds. Fifteen treatments were arranged in a Complete Randomized Design (CRD), including a control priming with water (T0), 25% (T1), 50% (T2), 75% (T3), 100% (T4) carrot root extract, 25%(T5), 50% (T6) , 75% (T7), 100% (T8) neem leaf extract, 25% (T9), 50% (T10), 75% (T11), 100% (T12) garlic clove extract, and 3% (T13), 5% Magnesium Sulfate ($MgSO_4$) (T14), each with 3 replicates were prepared to prime the okra seeds. Among the tested treatments, 50% carrot root extract, 100% neem leaf extract, 25% garlic clove extract and 3% $MgSO_4$, were identified as an appropriate concentration in enhancing germination of okra seeds in terms of germination percentage and increased radicle length ($p < 0.05$). Further, the selected five treatments (control primed with water (T0*), 50% carrot root extract (T2*), 100% neem leaf extract (T8*), 25% garlic clove extract (T9*) and 3% $MgSO_4$ (T13*)) each with five replicates were prepared and okra seeds were primed. A pot experiment was designed in a CRD and the primed seeds (24 hours) were sown under salinity stress condition (Sodium Chloride 100mM - 5.84 g Sodium Chloride in 1 l of irrigation water). Growth parameters of okra were recorded. All the data were statistically analyzed using Minitab 17.0 and differences between treatment means were compared using Tukey's test. In the pot experiment, okra seeds primed with 3% $MgSO_4$ (T13*) showed a significant enhancement ($p < 0.05$) of plant height, stem girth, leaf number, branch number and relative water content. The findings of this study suggest that compared to carrot, neem and garlic clove extract, 3% $MgSO_4$ acts as an effective priming agent in enhancing the growth performance of okra under salt stress.

Keywords: Okra, Plant Growth, Priming Agent, Salt Stress, Seed Germination

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Introduction

One of the most significant abiotic factors influencing agricultural production worldwide is salinity [1]. Salinity is caused by natural or man-made processes that accumulate dissolved salts in soil water, limiting plant growth. Extensive salinization of agricultural land leads to significant global economic losses [2]. High Na^+ concentrations disrupt osmotic equilibrium, inhibiting plant water uptake [3]. Salt stress influences multiple physiological processes in plant development, including the inhibition of cell division and cell elongation, leading to a reduction in shoot growth. Early flowering may reduce production in plants under salt stress since it reduces dry matter and increases the root-shoot ratio and leaf size [4].

Okra (*Abelmoschus esculentus*), an annual vegetable and herb, is widely cultivated in tropical and subtropical regions worldwide [5]. Salt-induced stress alters the concentrations of key bioactive compounds in okra, including antioxidants, vitamins, and essential minerals, potentially impacting both agricultural productivity and human nutrition [6].
Consequently, several effective strategies have been developed to enhance seed germination and improve tolerance to salt stress. Among these, seed priming is widely recognized. Seed priming is a pre-sowing treatment that involves partial hydration of seeds for a defined duration under controlled conditions, followed by re-drying to the original moisture content. This treatment triggers a range of biological, cellular, physiological, and molecular processes, which collectively enhance plant growth and resilience under abiotic stress conditions. Use of multiple agents to prime seeds has emerged as a viable strategy to increase plant resistance to stress. Plant extracts, hormones, organic compounds, ions, and chemicals such as potassium nitrate, hydrogen peroxide, ascorbic acid can all be used to prime seeds [7].

Carrot root extract induces salinity tolerance as it is rich in vitamins which are antioxidants and regarded as bio-regulators, thus using carrot root extract as a pre-soaking method efficiently overcomes salt stress in several plants such as cowpea. Therefore, this is a promising seed priming agent [8]. Garlic (*Allium sativum*) is a nutrient-rich extract with over 200 biological constituents, including enzymes, vitamins, and antioxidants [9]. Aqueous garlic extract (AGE) can activate plant defense responses [10]. AGE preparation is convenient and cost-effective, with minimal or no risks to consumers. Accordingly, it has been identified as an effective seed-priming agent capable of improving seed germination and facilitating early seedling development [11]. Neem (*Azadirachta indica*) leaf extract has been recognized as a highly promising agent for seed priming, enhancing both stress tolerance and uniformity in seed germination [12,13]. Priming seeds with $MgSO_4$ has been shown to mitigate the detrimental effects of salt stress in plants such as cotton. Mg^{2+} influences seed germination and early seedling development by modulating specific growth-promoting metabolites and enzymatic activities under saline conditions [14]. However, the effect of organic priming agents such as carrot root extract, garlic clove extract, neem leaf extract, and 3% and 5% $MgSO_4$ on enhancing the growth of okra MI5 variety under salt stress condition is not studied so far. Therefore, the present study aimed to evaluate the efficacy of seed priming using carrot root extract, garlic clove extract, neem leaf extract, and $MgSO_4$ and to find the suitable concentration of these priming agents in enhancing the germination and growth of okra under salt stress conditions.

Materials and Methods

Area of Study

A laboratory study was conducted at the Department of Biosystems Technology, Faculty of Technology, Eastern University of Sri Lanka from November 2024 to April 2025, to identify the optimal concentration of priming agents for okra (*Abelmoschus esculentus* L.) seed germination. Using the selected concentration, a subsequent pot experiment was performed in a home garden in Hatton, Nuwara Eliya District, Central Province, Sri Lanka (6°53′ N, 80°35′ E) to assess the impact of seed priming on germination and growth of okra under saline conditions.

Experimental Design

All the experiments were arranged in a completely randomized design (CRD).

Treatments

The laboratory experiment was carried out with fifteen treatments, each with 3 replicates.

Table 1: Treatment description for lab experiment

Treatments	Descriptions
T0	Control (water)
T1	25% extract from carrot roots
T2	50% extract from carrot roots
T3	75% extract from carrot roots
T4	100% extract from carrot roots
T5	25% neem leaf extract
T6	50% neem leaf extract
T7	75% neem leaf extract
T8	100% neem leaf extract
T9	25% garlic clove extract
T10	50% garlic clove extract
T11	75% garlic clove extract
T12	100% garlic clove extract
T13	3% $MgSO_4$
T14	5% $MgSO_4$

The pot experiment was carried out with the five selected treatments from the lab experiment with five replicates.

Table 2: Treatment description for pot experiment

Treatments	Descriptions
T0*	Seeds primed with water and pot irrigated with 100 mM NaCl (Control)
T2*	Seeds primed with 50% carrot root extract and pot irrigated with 100 mM NaCl.
T8*	Seeds primed with 100% neem leaf extract and pot irrigated with 100 mM NaCl.
T9*	Seeds primed with 25% garlic clove extract and pot irrigated with 100 mM NaCl.
T13*	Seeds primed with 3% $MgSO_4$ and pot irrigated with 100 mM NaCl.

Laboratory Experiment

This experiment aimed to identify the suitable concentration of priming agents (garlic clove extract, carrot root extract, neem leaf extract, and $MgSO_4$) for okra seed germination. The experiment was conducted in sterilized Petri dishes.

Preparation of Extracts

Carrot Root Extract (100%)

Fresh carrot roots were washed thoroughly with tap water. A total of 200 g of cleaned roots were cut into small pieces and homogenized with 640 mL of distilled water using an electric blender. The resulting mixture was filtered through muslin cloth, and the filtrate was adjusted to a final volume of 1 L with distilled water [15].

Garlic Clove Extract (100%)

Garlic cloves were cleaned, and the outer peels were removed. A total of 250 g of clove was combined with 250 mL of distilled water and subjected to three consecutive freeze-thaw cycles as freezing helps to maintain integrity of bioactive compounds while thawing allows for easier extraction. The cloves were then homogenized using an electric blender and filtered through muslin cloth. The filtrate was adjusted to a final volume of 1 L with distilled water [15].

Neem Leaf Extract (100%)

Neem leaves were collected from the vicinity of EUSL and rinsed thoroughly with distilled water. Excess surface moisture was removed by blotting the leaves on filter paper. A total of 25 g of fresh leaves was ground with 25 mL of distilled water to obtain the extract. The final volume was adjusted to 100ml with distilled water [16].

$MgSO_4$ (1M)

1 M $MgSO_4$ solution was prepared by dissolving 12.04 g of $MgSO_4$ in distilled water and made up to 100 ml, following the method described by [17]. Working solutions of 3% and 5% were prepared by diluting the stock solution to the required volume with distilled water.

Priming

Okra seeds of the 'MI5' variety were selected for the experiment. For seed priming, 2g of seeds were soaked in 10 ml (w/v: 1:5) [18] of fifteen treatments in 3 replicates for 24 hours. After that, the soaked seeds were washed 3-4 times in distilled water, and then the seeds were air-dried for 3 hours [19]. Upon completion of drying, the seeds were placed on filter paper within Petri dishes, which served as experimental replicates. Each replicate consisted of 29 seeds (After weighing the seeds to ensure consistency, it was determined that 29 seeds (a specific average weight) were the correct amount to ensure accuracy) positioned on the filter paper in a single Petri dish. A completely randomized design was used to place the petri dishes (CRD) inside the incubator at 25°C for 7 days. The moisture level was kept at the same level by adding two drops of water to each petri dish throughout the experiment. Germination percentage was evaluated after 24 hours and subsequently recorded until the end of the second day. Radicle (Length of the emerging root) and plumule length (Length of the emerging shoot) were measured using a ruler (cm) at two-day intervals, from the third to the seventh day.

Pot Experiment

Agronomic Practices

Okra variety MI5 was used in this experiment. For the experiment, black polybags (35.56 cm height and 35.56 cm diameter) were used. Every polybag contained a mixture of potting soil (Topsoil: loam at a ratio of 1:1), leaving a 5 cm gap at the top. Holes were made at the bottom of the polybags for drainage purposes. All the polybags were kept at a 60 cm × 60 cm interval. Based on the laboratory experimental result, among the tested treatments, 50% carrot root extract, 100% neem leaf extract, 25% garlic clove extract and 3% $MgSO_4$, were identified as appropriate concentration in enhancing germination of okra seeds in terms of germination percentage and increased radicle length. Thereafter, seeds were primed with those identified appropriate concentrations of solutions and sown directly into the filled poly bags (Three seeds per polybag) at a depth of around 1-2 cm.

In accordance with the recommendations of the Department of Agriculture, Sri Lanka, basal fertilization was applied two days before sowing, comprising 0.496 g of urea [$CO(NH_2)_2$], 0.937 g of triple superphosphate (TSP), and 0.248 g of muriate of potash (MOP) per experimental unit. After 2 weeks, 0.496g of urea and 0.248g MOP were added as top dressing. Pots were irrigated from seeding to germination stage, twice a day, in the early morning and late evening, and then it was reduced to once daily till the development of pods [20]. Salt stress (100 mM) was applied to the pots by dissolving 5.84 g sodium chloride in 1 L of irrigation water [21].

Data was collected at two-week intervals, beginning from the second week post-planting. Plant height (cm) was measured from the soil surface to the apical growing point using a ruler. Stem girth (cm) was determined by measuring the circumference at three different points along the stem using a thread, and the length of the thread was then measured using a ruler, and the mean value was calculated. The number of leaves and branches per plant were recorded. Relative water content was assessed following the method described by [21] using the below equation.

$$RWC\ (\%) = FW - \frac{DW}{TW - DW} \times 100$$

Data Analysis

The Minitab software application (version 17) was used to analyze all the data at a significance level of 5%. All the mean differences were analyzed using the Tukey range test.

Results and Discussion

Germination Percentage (%)

As shown in Table 3, the concentrations of priming agents tested did not exert a significant effect ($p > 0.05$) on okra seed germination within the first 24 hours. By contrast, the priming agents carrot root extract (T2), garlic clove extract (T9, T10, T11, T12) and neem leaf extract (T6, T8) significantly influenced ($p<0.05$) the germination percentage in the next 24 hours compared to the control.

Table 3: Germination percentage of okra seeds treated with different concentrations of priming agents measured at successive time intervals

Extracts	Treatments	After 24 hours (%)	After 48 hours (%)
Water (Control)	T0	56.30 ± 1.25^{a}	59.77 ± 1.15^{b}
	T1	44.82 ± 6.90^{a}	64.37 ± 7.54^{ab}
Carrot root	T2	40.23 ± 5.75^{a}	83.94 ± 6.11^{a}
Extract	T3	35.60 ± 11.70^{a}	74.53 ± 3.01^{ab}
	T4	60.90 ± 14.90^{a}	80.46 ± 4.60^{ab}
	***P* Value**	**0.334**	**0.029**
Water (Control)	T0	56.32 ± 1.15^{a}	59.77 ± 1.15^{b}
	T5	51.70 ± 10.50^{a}	82.76 ± 7.96^{ab}
Neem leaf	T6	43.70 ± 18.90^{a}	88.51 ± 3.04^{a}
Extract	T7	34.48 ± 7.18^{a}	82.76 ± 5.27^{ab}
	T8	47.12 ± 6.04^{a}	91.95 ± 4.60^{a}
	***P* Value**	**0.662**	**0.008**
Water (Control)	T0	56.32 ± 1.15^{a}	59.77 ± 1.15^{b}
	T9	60.92 ± 8.05^{a}	89.80 ± 1.86^{a}
Garlic clove	T10	59.77 ± 4.60^{a}	82.76 ± 3.98^{a}
Extract	T11	77.00 ± 5.75^{a}	87.36 ± 3.04^{a}
	T12	49.40 ± 19.60^{a}	89.65 ± 3.45^{a}
	***P* Value**	**0.442**	**0.000**
Water (Control)	T0	56.32 ± 1.15^{a}	59.77 ± 1.15^{a}
	T13	45.97 ± 9.41^{a}	81.61 ± 6.08^{a}
$MgSO_4$	T14	32.18 ± 3.04^{a}	71.30 ± 15.10^{a}
	***P* Value**	***0.066***	***0.328***

*Values represent the mean ± standard error of three replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

After 48 hours of incubation, among the different concentrations of carrot root extract tested, the 50% concentration (T2) showed a significantly higher germination percentage (83.94%) compared to the control (59.77%). For neem leaf extract, the 100% concentration (T8) recorded the highest germination percentage (91.95%), which was significantly higher than the control but not significantly different from the other neem extract concentrations tested. Similarly, treatment with 25% garlic clove extract (T9) resulted in a higher germination percentage (89.80%) compared to the control. However, no significant difference was observed among the various garlic extract treatments, indicating that all concentrations enhanced germination to a similar extent. In contrast, the $MgSO_4$ treatments (T13 and T14) did not show any significant difference in germination percentage compared to the control, suggesting that $MgSO_4$ had a limited effect on okra seed germination under the conditions tested.

Radicle and Plumule length (cm)

Radicle length

Radicle length was measured on the 3rd, 5th, and 7th days after sowing to evaluate the effects of different concentrations of carrot root, neem leaf, garlic clove extracts, and $MgSO_4$ on okra seed germination (Table 4).

Table 4: Effect of different concentration of priming agents on radicle length (cm) measured at various time intervals

Extracts	Treatments	3rd Day	5th Day	7th day
Water (Control)	T0	1.20 ± 0.20^{a}	1.50 ± 0.11^{b}	2.33 ± 0.23^{b}
	T1	1.56 ± 0.44^{a}	2.47 ± 0.41^{ab}	3.30 ± 0.18^{ab}
Carrot root	T2	3.14 ± 0.41^{b}	3.39 ± 0.45^{ab}	4.04 ± 0.54^{a}
Extract	T3	2.92 ± 0.57^{a}	3.69 ± 0.66^{a}	3.51 ± 0.31^{ab}
	T4	2.96 ± 0.42^{a}	3.56 ± 0.19^{a}	3.86 ± 0.23^{ab}
	***P* Value**	**0.026**	**0.019**	**0.032**
Water (Control)	T0	1.20 ± 0.20^{b}	1.50 ± 0.11^{c}	2.33 ± 0.23^{c}
	T5	2.02 ± 0.44^{ab}	2.55 ± 0.26^{b}	3.43 ± 0.22^{ab}
Neem leaf	T6	1.81 ± 0.26^{b}	2.56 ± 0.14^{b}	2.90 ± 0.15^{bc}
Extract	T7	2.23 ± 0.09^{ab}	2.47 ± 0.05^{b}	3.50 ± 0.16^{ab}
	T8	3.16 ± 0.24^{a}	3.76 ± 0.08^{a}	3.96 ± 0.06^{a}
	***P* Value**	**0.007**	**0.000**	**0.001**
Water (Control)	T0	1.20 ± 0.20^{a}	1.50 ± 0.11^{b}	2.33 ± 0.23^{b}
	T9	3.48 ± 0.32^{a}	3.72 ± 0.20^{a}	4.10 ± 0.23^{a}
Garlic clove	T10	2.56 ± 1.12^{a}	3.55 ± 0.72^{a}	3.99 ± 0.50^{a}
Extract	T11	3.08 ± 0.32^{a}	3.62 ± 0.19^{a}	3.78 ± 0.17^{a}
	T12	2.84 ± 0.33^{a}	3.44 ± 0.17^{a}	3.77 ± 0.12^{a}
	***P* Value**	**0.125**	**0.007**	**0.008**
Water (Control)	T0	1.20 ± 0.20^{a}	1.50 ± 0.11^{b}	2.33 ± 0.23^{b}
	T13	3.21 ± 0.33^{b}	3.42 ± 0.32^{a}	3.84 ± 0.36^{a}
$MgSO_4$	T14	2.24 ± 0.36^{a}	2.96 ± 0.28^{ab}	3.82 ± 0.16^{a}
	***P* Value**	**0.030**	**0.001**	**0.007**

*Values represent the mean ± standard error of three replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

After 3 days, all the priming treatments showed a positive influence on radicle length compared to the control. Among the carrot root extract treatments, the 50% concentration (T2) recorded the highest mean radicle length (3.14 cm), which was significantly higher ($p = 0.026$) than the control (1.20 cm). Similarly, for neem leaf extract, the 100% concentration (T8) produced the highest radicle length (3.16 cm), which was significantly higher than T6 and the control. Garlic clove extract treatments also increased radicle length, although the differences were not statistically significant at this stage ($p = 0.125$). $MgSO_4$ treatments showed significant improvement in radicle length ($p = 0.030$), with T13 (3.21 cm) producing a notable increase over the control.

By the 5th day, the growth differences became more distinct. The highest radicle lengths were observed in treatments with carrot root extract (T3 = 3.69 cm), neem leaf extract (T8 = 3.76 cm), and garlic clove extract (T9 = 3.72 cm), all significantly higher than the control ($p < 0.05$). Among the $MgSO_4$ treatments, T13 (3.42 cm) showed a marked increase compared to the control (1.50 cm), indicating that Mg^{2+} ions may contribute to early seedling vigor.
After 7 days, a consistent trend was observed, where all treated seeds produced longer radicle than the control (2.33 cm). The 50% carrot root extract (T2 = 4.04 cm), 100% neem leaf extract (T8 = 3.96 cm), and 25% garlic clove extract (T9 = 4.10 cm) exhibited the greatest seedling lengths, with statistically significant differences ($p < 0.05$) compared to the control. $MgSO_4$ treatments (T13 = 3.84 cm; T14 = 3.82 cm) also showed significantly improved growth ($p = 0.007$).

Overall, the results indicate that seed priming with natural extracts, particularly carrot root (50%), neem leaf (100%), and garlic clove (25%), markedly enhanced okra radicle growth during early stages. This improvement could be attributed to the presence of growth-promoting compounds such as vitamins, phenolics, and antioxidants in these extracts, which may enhance metabolic activity, enzyme function, and nutrient uptake during germination and early growth [22,23,24]. $MgSO_4$ also promoted radicle elongation, possibly by improving cellular metabolism and photosynthetic activity through magnesium's role in chlorophyll synthesis [25].

Plumule length

The effects of different concentrations of priming agents on okra plumule length are presented in Table 5. On the 3rd, 5th, and 7th days after sowing, the priming treatments exhibited no significant influence on plumule length ($p > 0.05$).

The result indicated that varying concentrations of different priming agents had no significant effect on plumule length. This may suggest that plumule elongation is not sensitive to these specific priming agents. However, plumule length increased with time in each treatment group.

Table 5: Effect of different concentration of priming agents on plumule length (cm) measured at various time intervals

Extracts	Treatments	3rd Day	5th Day	7th day
Water (Control)	T0	0.87 ± 0.13^a	1.43 ± 0.08^a	1.67 ± 0.08^a
	T1	0.90 ± 0.05^a	1.33 ± 0.14^a	1.64 ± 0.06^a
Carrot root	T2	1.00 ± 0.02^a	1.60 ± 0.10^a	1.73 ± 0.08^a
Extract	T3	0.92 ± 0.08^a	1.40 ± 0.19^a	1.70 ± 0.02^a
	T4	0.96 ± 0.08^a	1.48 ± 0.18^a	1.65 ± 0.11^a
	***P* Value**	**0.824**	**0.775**	**0.938**
Water (Control)	T0	0.87 ± 0.13^a	1.43 ± 0.08^a	1.67 ± 0.08^a
	T5	0.89 ± 0.02^a	1.16 ± 0.12^a	1.38 ± 0.13^a
Neem leaf	T6	1.04 ± 0.06^a	1.57 ± 0.09^a	1.66 ± 0.07^a
Extract	T7	1.07 ± 0.03^a	1.58 ± 0.10^a	1.71 ± 0.03^a
	T8	1.01 ± 0.02^a	1.43 ± 0.09^a	1.63 ± 0.16^a
	***P* Value**	**0.247**	**0.078**	**0.280**

Water (Control)	T0	0.87 ± 0.13^{a}	1.43 ± 0.08^{a}	1.67 ± 0.08^{a}
	T9	1.11 ± 0.01^{a}	1.54 ± 0.07^{a}	1.77 ± 0.10^{a}
Garlic clove	T10	0.88 ± 0.09^{a}	1.35 ± 0.12^{a}	1.62 ± 0.08^{a}
Extract	T11	0.91 ± 0.07^{a}	1.45 ± 0.17^{a}	1.65 ± 0.07^{a}
	T12	1.00 ± 0.07^{a}	1.43 ± 0.11^{a}	1.49 ± 0.11^{a}
	***P* Value**	**0.343**	**0.844**	**0.380**
Water (Control)	T0	0.87 ± 0.13^{a}	1.43 ± 0.08^{a}	1.67 ± 0.08^{a}
	T13	1.03 ± 0.01^{a}	1.34 ± 0.07^{a}	1.57 ± 0.02^{a}
$MgSO_4$	T14	0.99 ± 0.05^{a}	1.25 ± 0.03^{a}	1.46 ± 0.04^{a}
	***P* Value**	**0.450**	**0.272**	**0.097**

*Values represent the mean ± standard error of three replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

Pot Experiment Results

Plant height (cm)

The effects of different concentrations of priming agents on okra plant height are presented in Table 6.

Table 6: Variation in plant height (cm) of okra in response to different concentrations of priming agents at weekly growth intervals

Extracts	Treatments	2^{nd} Week(cm)	4^{th} Week(cm)	6^{th} Week(cm)	8^{th} Week(cm)
Water (Control)	T0*	11.20 ± 0.93^{b}	12.88 ± 1.13^{b}	21.86 ± 2.11^{b}	28.14 ± 2.18^{b}
50% Carrot root Extract	T2*	12.60 ± 0.80^{ab}	17.30 ± 2.45^{ab}	27.40 ± 0.79^{ab}	35.02 ± 1.54^{ab}
100% Neem leaf Extract	T8*	12.38 ± 1.17^{ab}	13.54 ± 1.54^{b}	24.96 ± 2.21^{ab}	31.92 ± 2.35^{ab}
25% Garlic clove Extract	T9*	12.16 ± 0.97^{ab}	16.06 ± 0.88^{ab}	24.56 ± 2.44^{ab}	30.58 ± 1.53^{ab}
3% $MgSO_4$	T13*	16.00 ± 0.82^{a}	20.26 ± 1.47^{a}	31.32 ± 2.01^{a}	38.00 ± 2.67^{a}
	***p* value**	**0.021**	**0.024**	**0.036**	**0.029**

*Values represent the mean ± standard error of five replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

In the 2^{nd} week among the priming treatments, 3% $MgSO_4$ (T13*) recorded the highest mean plant height (16.00 cm), which was significantly higher than the control (11.20 cm) under salt stress. Similarly, by the 4^{th},6^{th} and 8^{th} weeks, T13* exhibited significantly highest ($p < 0.05$) plant height (20.26 cm, 31.32 cm, 38.00 cm respectively) compared to the control under salt stress. These findings support the results of [26], who reported enhanced plant height in okra when seeds were primed with $MgSO_4$. This improvement could be attributed to the function of magnesium sulphate ($MgSO_4$) in boosting plant height by improving nutrient absorption, particularly of nitrogen, which is essential for photosynthesis and protein synthesis.

Effect of priming agents on leaf number

Table 7 presents the effect of different priming agents on the leaf number of okra plants.

Seed priming treatments significantly ($p < 0.05$) influenced leaf production under salt stress.

In the 2nd week, among the treatments, 3% $MgSO_4$ (T13*) exhibited the highest mean leaf count, which was significantly higher than ($p = 0.000$) other treatments and the control. By the 4th week T13* (5.2 cm) exhibited the greatest leaf count, with statistically significant differences ($p < 0.05$) compared to the control. After 6th and 8th weeks, T13* consistently showed the highest mean leaf count (7.0, and 9.4, respectively), which was significantly higher than T8*, T9* and the control. These results are consistent with the findings of [27], who reported that okra plants subjected to seed priming with 3% $MgSO_4$ showed a significant increase in leaf production under salt stress condition. Which could be the reason that, Mg^{2+} is an essential component of chlorophyll, which enables photosynthesis and promotes growth and biomass buildup [28].

Table 7: Effects of varying priming treatments on the number of leaves of the okra plant at different week intervals

Extracts	Treatments	2nd Week	4th Week	6th Week	8th Week
Water (Control)	T0*	2.2 ± 0.2^{b}	3.0 ± 0.0^{b}	4.0 ± 0.0^{c}	5.2 ± 0.2^{c}
50% Carrot root Extract	T2*	2.8 ± 0.2^{b}	4.2 ± 0.3^{ab}	6.4 ± 0.2^{ab}	8.0 ± 0.3^{ab}
100% Neem leaf Extract	T8*	2.4 ± 0.2^{b}	4.2 ± 1.5^{ab}	5.2 ± 1.4^{bc}	6.2 ± 0.3^{bc}
25% Garlic clove Extract	T9*	2.6 ± 0.2^{b}	4.4 ± 1.5^{ab}	5.6 ± 0.2^{b}	6.0 ± 0.7^{c}
3% $MgSO_4$	T13*	3.8 ± 0.2^{a}	5.2 ± 0.2^{a}	7.0 ± 0.3^{a}	9.4 ± 0.5^{a}
	***p* value**	**0.000**	**0.016**	**0.000**	**0.000**

*Values represent the mean ± standard error of five replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

Number of branches per plant

The effect of different priming agents on the number of branches of okra plants is shown in Table 8. A significant influence ($p<0.05$) was observed by the priming agents in the number of branches of okra plants grown under salt stress condition.

Table 8: Effects of varying priming agent concentrations on each plant's number of branches at various week intervals

Extracts	Treatments	4th Week	6th Week	8th Week
Control	T0*	0.4 ± 0.4^{b}	2.0 ± 0.0^{b}	2.2 ± 0.2^{b}
50% Carrot root Extract	T2*	1.2 ± 0.5^{ab}	2.0 ± 0.0^{b}	2.8 ± 0.2^{b}
100% Neem leaf Extract	T8*	0.0 ± 0.0^{b}	2.0 ± 0.0^{b}	2.4 ± 0.3^{ab}
25% Garlic clove Extract	T9*	0.4 ± 0.4^{b}	2.2 ± 0.2^{ab}	2.4 ± 0.3^{ab}
3% $MgSO_4$	T13*	2.0 ± 0.0^{a}	2.6 ± 0.3^{a}	3.2 ± 0.2^{a}
	***p* value**	**0.003**	**0.028**	**0.030**

*Values represent the mean ± standard error of five replicates. Mean values in a row having dissimilar letters indicate significant differences at a 5% level of significance according to Tukey's HSD Test.

In the 4th week, T13* recorded the highest mean branch count (2.0), which was significantly higher than the control under salt stress. By the 6th week, T13* showed significant improvement in branch count (2.6) compared to T2*, T8* and the control under salt stress. In the 8th week T13* exhibited highest mean branch count (3.2), with statistically significant differences (p = 0.030) compared to the control under salt stress.

Stem girth (cm)

Table 9 illustrates how various priming treatments affect the stem girth of okra plants. The priming treatments have significant impact on weekly stem girth values under salt stress.

Table 9: Effects of varying priming agent concentrations on the stem girth of the okra plant at different week intervals

Treatments	2nd Week (cm)	4th Week (cm)	6th Week (cm)	8th Week (cm)
T0*	0.77 ± 0.06^{b}	1.25 ± 0.05^{b}	1.70 ± 0.11^{b}	2.05 ± 0.14^{b}
T2*	0.84 ± 0.04^{b}	1.42 ± 0.04^{b}	1.84 ± 0.06^{ab}	2.11 ± 0.12^{ab}
T8*	1.00 ± 0.09^{ab}	1.45 ± 0.14^{b}	2.09 ± 0.12^{ab}	2.62 ± 0.11^{ab}
T9*	1.22 ± 0.10^{a}	1.66 ± 0.14^{ab}	2.04 ± 0.13^{ab}	2.65 ± 0.23^{ab}
T13*	1.23 ± 0.09^{a}	1.97 ± 0.09^{a}	2.29 ± 0.11^{a}	2.79 ± 0.14^{a}
***p* value**	**0.001**	**0.001**	**0.015**	**0.010**

The mean ± standard error of five replicates is represented by the values. According to Tukey's HSD Test, mean values in a row with distinct letters indicate significant differences at a 5% level of significance.

According to Table 9, in the 2nd week, T13* showed highest stem girth (1.23 cm), which was significantly higher than T2* and the control T0* (0.77 cm) under salt stress. In the 4th week significantly highest stem girth was recorded in T13* (1.97 cm) compared to T2*, T8* and the control under salt stress. By the 6th and 8th weeks, T13* showed notable increase in stem girth (2.29 cm, and 2.79 cm respectively), which were significantly higher than the control (1.70 cm, and 2.05 cm respectively) under salt stress. These results were on par with the findings of [29] and this could be due to the role of Magnesium in increasing plant biomass [30].

Relative Water Content (%)

According to Table 10, T13* (3% $MgSO_4$) showed a significantly highest RWC with an average of 68.27% compared to the control (59.90%). This demonstrates a marked increase compared to the control, highlighting the effectiveness of 3% $MgSO_4$ in maintaining the highest RWC in leaf tissues under salt stress. The findings of [31] also agreed with these results, which could be the reason that, magnesium and sulphate ions aid in maintaining ion balance and enhancing the general stability of cell membranes which assist the plant to stay hydrated under salt stress condition.

Table 10: Effects of varying priming agent concentrations on the relative water content of okra leaves

Treatments	Relative Water Content (%)
T0*	59.90 ± 1.01^{b}
T2*	64.66 ± 2.03^{ab}
T8*	65.61 ± 1.85^{ab}
T9*	62.03 ± 1.71^{ab}
T13*	68.27 ± 1.66^{a}
***p* value**	**0.021**

The mean ± standard error of five replicates is represented by the values. According to Tukey's HSD Test, mean values in a column with distinct letters indicate significant differences at a 5% level of significance.

Conclusion

As demonstrated by the findings of the laboratory experiment, radicle length was significantly enhanced by seed priming, so as germination percentage at the later stage, though plumule length was not significantly influenced by the priming agents. Results of the pot experiment revealed that the growth of *Abelmoschus esculentus* L. (okra) under salt stress was significantly ($p<0.05$) affected by seed priming with various priming agents, Among the treatments, 3% $MgSO_4$ led to significant improvements in height of the plant, relative water content, stem girth, number of leaves, and number of branches. Based on the results, 3% $MgSO_4$ could be recommended for use to prime okra seeds in order to enhance the growth performance under salt stress.

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Author Contribution

All the authors equally contributed to this study.

Disclosure of Conflicts of Interest

No conflicts of interest are disclosed by the authors.

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Assessment of plant diversity and the floristic inventory of the main site (Oluvil) of the South Eastern University of Sri Lanka

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Abstract

The main site of the South Eastern University of Sri Lanka is situated in Oluvil in the Ampara district of Sri Lanka in the climatic region 'Dry Zone'. It spans over 72.8 ha bound by the sea on its eastern side and a stream on its northern side could be made into a biodiversity rich sustainable urban ecosystem. A part of the site was under coconut (*Cocos nucifera)* cultivation and *Azadirachta indica*, *Borassus flabellifer* and *Terminalia arjuna* in considerable numbers in rest of the land. Various plants are being introduced as part of landscaping activities since 1995 with the commencement of the university aiming to provide better social, ecological, and personal benefits. The site was severely affected by the 2004 Tsunami and undergoes flooding occasionally during monsoonal rains. In addition infrastructure development activities for the university are being carried out continuously. This study aimed to prepare an inventory of plants in the site as it is useful in decision making on land use and biodiversity conservation. A complete census of all plants, except naturally grown grasses and herbs, was done by marking and counting method. A total of 125 plant species were found out of which 101 species are medicinal plants and 17 are fruit plants and 19 with some timber value. Only 30 species are native to Sri Lanka and among them only 2 are 'Near threatened' and 5 are 'Vulnerable'. Incorporating more endemic, threatened and vulnerable native species in future landscape activities would make it more biodiversity conservation oriented while enhancing cultural ecosystem services.

Key words: Complete census, medicinal plants, native plants, plant inventory, South Eastern University of Sri Lanka.

Introduction

The main site of South Eastern University of Sri Lanka is situated in Oluvil (longitude 81.8606° E and latitude 7.2944° N) in the Ampara district which is in the climatic region 'Dry Zone' (Figure 1). It spans over 72.8 ha with a flat terrain of an average altitude of 6.26 m and bound by the 'Gal- Oya' or 'Kali-Odai' stream on the northern side, sea on the eastern side, Oluvil village on the southern side and the Akkaraipaththu-Kalmunai highway (A4 highway) on the western side (Figure 2.).

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Figure 1: Location of the site (https://en.wikipedia.org/wiki/South_Eastern_University_of_Sri_Lanka#/map/0)

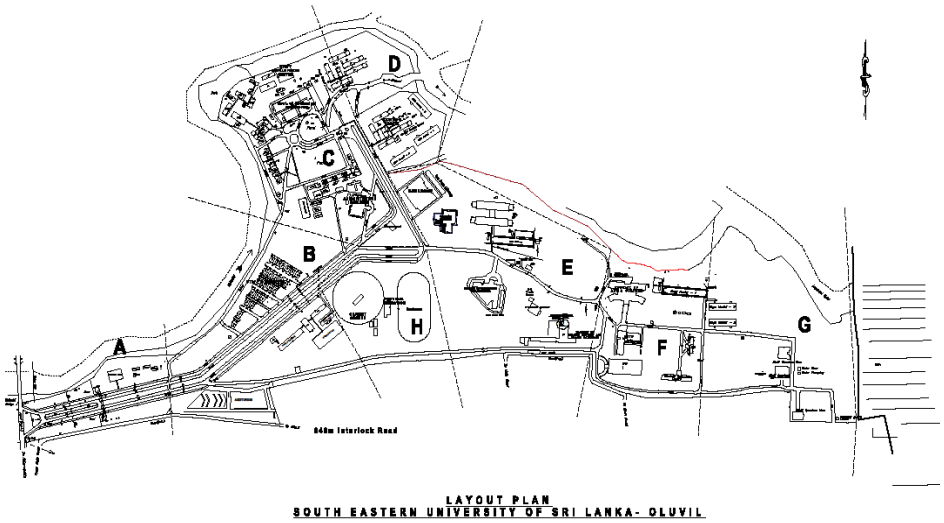

Figure 2: Map of main site of the South Eastern University of Sri Lanka (*Credit:* Works Department, South Eastern University of Sri Lanka)

The average annual precipitation is 212.02 mm received mainly from the 'North-East monsoon during October to February ('Maha' season), average temperature 25.76 - 31.27°C [1,2].

The site has been under human influence for a long period until landscaping activities commenced with setting aside the land for the university in 1995. As an environment modified for human activities this can be categorized into an urban ecosystem [3]. The well-functioning urban ecosystems, with their services and biodiversity, are an important pillar of the sustainable development of urban societies [4]. A part of the land was under coconut (*Cocos nucifera*) cultivation and the other prominent plants found were *Terminalia arjuna* along the stream bank and *Azadirachta indica and Borassus flabellifer* scattered in the rest of the land. Landscaping activities commenced with the aim of enhancing natural beauty, creating outdoor functional spaces coupled with enhancing biodiversity and conservation. Benefits of biodiversity and structural complexity in planting within urban vegetation include the creation of habitats and increased climate resilience, as well as positive impacts on human health and wellbeing [3]. A variety of plants both native and exotic species have been introduced and some natives have been

introduced in large numbers as seedlings either nursery raised or obtained/purchased from other sources. The site was severely affected by the 2004 Tsunami and occasionally undergoes severe flooding during monsoonal rains. In addition, the land is being utilized for various infrastructure developments of the University. Chiarucci and Palmer (2002) quoting others: [5-8] reported that the species lists and species richness of park-size units would be useful in decision making on land use and biodiversity conservation. In line with this perspective, the present study aimed to inventory the plant species excluding naturally growing grasses and herbs within the main campus of the South Eastern University of Sri Lanka.

Methodology

Sampling site

The whole 72.8 ha of the main site of South Eastern University of Sri Lanka situated in Oluvil (longitude 81.8606° E and latitude 7.2944° N) in the Ampara district (Figure 2).

Sampling method

A complete census [9] of all the plants (except naturally grown grasses and herbs) was done during latter half of 2021 and the plants were marked to avoid recounting. The census was done block by block in the 7 blocks demarcated for infrastructure development purposes (Figure 2). These main blocks were divided into smaller blocks using other demarcations like roads, fences etc. were available, for convenience of census.

Plant identification

The morphological features of the plants were recorded and the plants were identified using the, expertise knowledge and literature 'A field guide to the common trees and shrubs of Sri Lanka' [10] and the Ayurvedic Medicinal Plants of Sri Lanka Compendium Version 3 [11].

Data collection

The vernacular names and anthropo-ecological values of the plants, were obtained from the same literature mentioned in above 2.3. When these data were not available in those two sources they were obtained from "Google" (google.com/search) browser during the period of 1st to 6th of September 2025. Prompts used to obtain the vernacular names from Google were the 'scientific name of the plant' together with required 'language name' i.e. 'Sinhala name' or 'Tamil name' or 'English name'. The anthropo-ecological uses of the plants were obtained by giving the prompts, the 'scientific name' of the plant and the term 'uses'.

Data analysis

The anthropo-ecological values of the plants based on the above literature were evaluated.

Results and Discussion

This study found a total of 125 plant species in the site which includes 30 (24%) native species (Figure 3) which is 0.97% of the angiosperms recorded in Sri Lanka [12] including one endemic to Sri Lanka namely *Oncosperma fasciculatum* and the rest were exotics (Table 1).

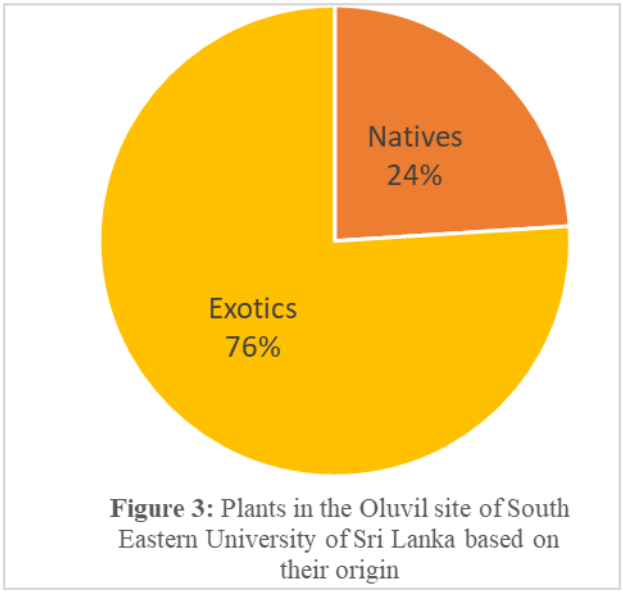

Figure 3: Plants in the Oluvil site of South Eastern University of Sri Lanka based on their origin

All these natives and the 43 exotics except *Strychnos potatorum* are recorded as common plants of Sri Lanka [10] and hence all these exotics can be considered as naturalized species which is 10.2% of the recorded common plants in the country. The remaining exotics (52 species) have been planted for their aesthetic/landscape value.

Among the plants, 101 species are medicinal plants, 17 are fruit plants and 19 having some timber value (Figure 4). The plants consists of a combination of 71 tree species, 22 shrub species, 16 palm species and 7 climbers (Figure 5) of different forms and sizes which contribute to the structural complexity that would provide niches for different animal life contributing to a rich biodiversity which in turn enhances the 'cultural ecosystem services' (CES) i.e "the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences'' [13]. Being a university where the students and staff live a busy and stressful life, an ecosystem with a higher CES would contribute immensely to physical and mental health [14,15] of the university community.

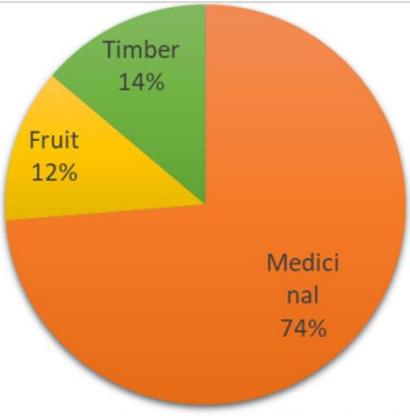

Figure 4: Plants in the Oluvil site of South Eastern University of Sri Lanka based on their uses

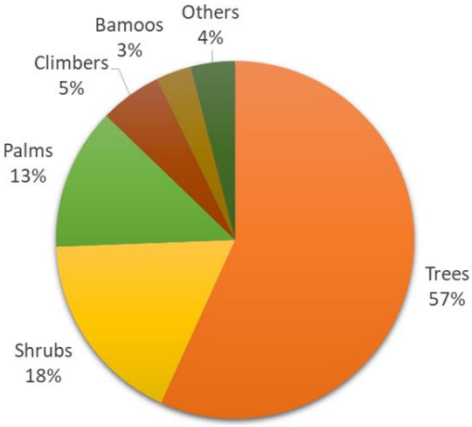

Figure 5: Types and numbers of plants in the Oluvil site of South Eastern University of Sri Lanka

Among the native species in the site, only 02 belong to the 'Near threatened' category, 05 considered to be 'vulnerable' and the other 25 are of 'least concerned' according to 'The National Red List-2020' [12] Including native plants with structurally complex planting has been shown useful in increasing the species richness in an urban environment [16]. Addressing the needs of both people and nature facilitates effective, integrated conservation [17] to achieve sustainable and equitable solutions to the current biodiversity crisis [18].

Table 1: Plant species in the South Eastern University of Sri Lanka

Serial number	Scientific name	Family	Vernacular (common) names			Number of plants [1]	Phytogeography [2]	Conservation status [3]	Common uses
			Sinhala	Tamil	English				
Fruit Trees									
1	*Anacardium occidentale*	Anacardiaceae	Kaju	Mundiri	Cashew	75	NE		Fruit edible, medicine
2	*Annona reticulata*	Annonaceae	Weli atha	Ramsitha	Custard apple	1	NE		Fruit edible, medicine, insecticidal
3	*Annona squamosa*	Annonaceae	Seeni atha	Seetha pazham	Sugar apple	5	NE		Fruit edible, medicine
4	*Artocarpus heterophyllus*	Moraceae	Kos	Pila	Jak	29	NE		Fruit edible, medicine, timber, fodder
5	*Averrhoa carambola*	Oxalidaceae	Kamaranga	Tamanta	Star fruit	7	EX		Fruit edible, medicine
6	*Cordia dichotoma*	Boraginaceae	Lolu	Naruvili	Indian cherry	4	EX		Fruit edible, medicine
7	*Elaeocarpus serratus*	Elaeocarpaceae	Veralu	Karai	Ceylon olive	3	NV	LC	Fruit edible, medicine
8	*Ficus racemosa*	Moraceae	Attikka	Atti	Fig	7	NV	LC	Fruit edible, medicine
9	*Ficus virens*	Moraceae	Kaluwalla	Kurugatti	White fig	8	NV	LC	Fruit edible, ornamental/ shade, fodder
10	*Garcinia mangostana*	Clusiaceae	Mangus	Mangus	Mangosteen	1	NE		Fruit edible, medicine
11	*Mangifera indica*	Anacardiaceae	Amba	Ma	Mango	257	NE		Fruit edible, medicine, timber
12	*Muntingia calabura*	Muntingiaceae	Jam gaha	Jam maram	Jam tree	3	NE		Fruit edible, medicine
13	*Nephelium lappaceum*	Sapindaceae	Rambutan	Rambutan	Rambutan	1	NE		Fruit edible, medicine, cosmetics
14	*Phyllanthus acidus*	Phyllanthaceae	Rata nelli	Siru nelli	Star gooseberry	7	NE		Fruit edible, medicine
15	*Phyllanthus emblica*	Phyllanthaceae	Nelli	Topu nelli	Amla	2	NV	VU	Fruit edible, medicine
16	*Psidium cattleyanum*	Myrtaceae			Strawberry guava	6	EX		Fruit edible
17	*Psidium guajava*	Myrtaceae	Pera	Goyya pazham	Guava	37	NE		Fruit edible, medicine

18	*Punica granatum*	Lythraceae	Delum	Mathulai	Pomegranate	21	NE		Fruit edible, medicine
19	*Schleichera oleosa*	Sapindaceae	Kone	Puvu	Ceylon oak	3	NV	LC	Fruit edible, medicine, timber
20	*Spondias dulcis*	Anacardiaceae	Ambarella	Ampallai	Ambarella	15	NE		Fruit edible, medicine
21	*Syzygium cumini*	Myrtaceae	Madan	Naval	Black plum	10	NV	LC	Fruit edible, medicine
22	*Syzygium samarangense*	Myrtaceae	Pini jambu		Wax jambu	8	EX		Fruit edible, medicine
23	*Tamarindus indica*	Fabaceae	Siyambala	Puli	Tamarind	7	NE		Fruit edible, medicine, ornamental
24	*Ziziphus mauritiana*	Rhamnaceae	Masan	Ilantai	Indian plum	1	NV	LC	Fruit edible, medicine, fodder
Other trees									
25	*Acacia auriculiformis*	Fabaceae	Acacia	Kaththik karuwel	Ear leaf acacia	58	EX		Erosion control, ornamental
26	*Adenanthera pavonina*	Fabaceae	Madatiya	Manjadi	Jumble bead	3	NV	LC	Medicine, timber, ornamental/ shade
27	*Albizia lebbeck*	Fabaceae	Mara	Vakai	Lebbek	16	NV	NT	Timber, medicine
28	*Araucaria columnaris*	Araucariaceae			Cook's pine	1	EX		Medicine, ornamental
29	*Azadirachta indica*	Meliaceae	Kohomba	Vembu	Margosa	929	NE		Medicine, shade, insecticide
30	*Berrya cordifolia*	Malvaceae	Halmilla	Chavandalai	Trincomalee wood	49	NV	LC	Timber, ship building
31	*Cassia fistula*	Fabaceae	Ehela	Tiru kontai	Indian laburnum	6	NV	LC	Medicine, ornamental
32	*Cassia roxburghii*	Fabaceae	Ratu wa	Vakai	Red cassia	4	NV	LC	Medicine, ornamental
33	*Cassia spectabilis*	Fabaceae	Kaha kona	Munjal kona	Popcorn tree	8	NE		Medicine, ornamental
34	*Casuarina equisetifolia*	Casuarinaceae	Kasa	Chavukku	Casuarina	35	NE		Timber, erosion control
35	*Chloroxylon swietenia*	Rutaceae	Burutha	Muthirai	Satin wood	5	NV	VU	Timber, medicine
36	*Clusia fluminensis*	Clusiaceae			Dwarf clusia	7	EX		Ornamental
37	*Cordia sp.*	Boraginaceae.				9			
38	*Couroupita guianensis*	Lecythidaceae	Sal	Nagalingam maram	Cannon ball tree	23	NE		Medicine, ornamental
39	*Cupressus macrocarpa*	Cupressaceae			Monterey cypress	71	NE		Ornamental, christmas tree
40	*Delonix regia*	Fabaceae	Mai mal	Mayaram	Flame tree	5	NE		Medicine, ornamental/ shade
41	*Diospyros ebenum*	Ebenaceae	Kaluwara	Karunkali	Ceylon ebony	47	NV	VU	Furniture making, medicine
42	*Diospyros malabarica*	Ebenaceae	Thimbiri	Panichchai	Malabar ebony	1	NV	LC	Timber, medicine
43	*Eucalyptus*	Myrtaceae		Neelagiri	Murray red	3	NE		Timber,

	camaldulensis			thailamaram	gum				medicine
44	*Ficus benghalensis*	Moraceae	Nuga	Al	Banyan	17	NV	LC	Medicine, ornamental/shade, sacred
45	*Ficus benjamina*	Moraceae	Walu nuga	Nintamaravakai	Benjamin tree	37	NE		Medicine, ornamental/shade
46	*Ficus religiosa*	Moraceae	Bo	Arachu	Sacred fig	1	NE		Medicine, sacred
47	*Filicium decipiens*	Sapindaceae	Pihimbiya	Chittira vempu	Fern tree	33	NV	LC	Medicine, timber
48	*Gliricidia sepium*	Fabaceae	Weta hiriya	Kona	Gliricidia	7	NE		Soil fertility, fodder, live fence
49	*Hydnocarpus venenatus*	Achariaceae	Makulu	Makul		1	NV	LC	Medicine
50	*Khaya senegalensis*	Meliaceae	Kaya	African mahogany	African mahogany	516	EX		Timber, medicine, landscaping
51	*Lagerstroemia speciosa*	Lythraceae	Murutha	Pu muruthu	Queen of flowers	2	NV	LC	Medicine, ornamental
52	*Manilkara* sp.	Sapotaceae				4			
53	*Mesua ferrea*	Calophyllaceae	Na	Naka	Iron wood	1	NV	LC	Medicine, timber, ornamental
54	*Millettia pinnata*	Fabaceae	Mangul karanda	Pungai	Seashore mempari	4	EX		Medicine, insecticide,
55	*Morinda citrifolia*	Rubiaceae	Ahu	Manchavanna	Indian mulberry	251	NV	LC	Medicine
56	*Nauclea orientalis*	Rubiaceae	Bak mee	Vammi	Bur tree	14	NV	LC	Medicine, fruit edible
57	*Pithecellobium dulce*	Fabaceae	Andara	Kara puli	Madras thorn	4	NE		Medicine, shade, fodder
58	*Plumeria obtusa*	Apocynaceae	Araliya	Nela Sampangi	Temple flower	29	NE		Medicine, ornamental
59	*Polyalthia longifolia*	Annonaceae	Owila	Illupai	False ashoka	77	NE		Medicine, ornamental
60	*Pterocarpus indicus*	Fabaceae	Wal ehela	Kengei	Andaman red wood	22	NE		Ornamental/shade, live fencing
61	*Pterocarpus marsupium*	Fabaceae	Gammalu	Utera-Venkai	Malabar kino	10	NV	NT	Medicine
62	*Pterospermum suberifolium*	Malvaceae	Velangu	Vilanku	Cork leaved bayur	1	NV	LC	Medicine, ornamental/shade
63	*Sapindus* sp.	Sapindaceae				3			
64	*Strychnos nux-vomica*	Loganiaceae	Goda kaduru	Kanchurai	Strychnine tree	1	NV	LC	Timber, seed-poisonous
65	*Strychnos potatorum*	Loganiaceae	Ingini	Tetta	Clearing nut tree	1	NV	LC	Medicine, seeds for water purification
66	*Swietenia mahagoni*	Meliaceae	Mahogany	Magahani	Cuban mahogany	66	NE		Timber, medicine
67	*Tabebuia rosea*	Bignoniaceae	Rosa horane	Vasantha rani	Pink tabebuia	17	NE		Timber, medicine, ornamental
68	*Tectona grandis*	Lamiaceae	Theka	Thekku	Teak	173	NE		Timber, medicine
69	*Terminalia arjuna*	Combretaceae	Kumbuk	Marutu	Arjun tree	431	NV	LC	Timber, medicine
70	*Terminalia bellirica*	Combretaceae	Bulu	Tanti	Myrabalans	42	NV	LC	Medicine, timber, shade
71	*Terminalia catappa*	Combretaceae	Kottamba	vadumai	Indian almond	6	NE		Medicine, ornamental/shade
Palms									
72	*Adonidia merrillii*	Arecaceae			Manila palm	44	EX		Ornamental
73	*Bismarckia nobilis*	Arecaceae			Silver	2	EX		Ornamental

	(small)				bismarc palm				
74	*Borassus flabellifer*	Arecaceae	Thal	Panai	Palmyra	884	NE		Medicine, food/beverage, timber
75	*Cocos nucifera*	Arecaceae	Pol	Thennai	Coconut	1604	NE		Medicine, food/beverage, timber
76	*Cyrtostachys renda*	Arecaceae	Niyan pera		Lip stick palm	47	EX		Ornamental
77	*Dypsis decaryi*	Arecaceae			Triangle palm	2	EX		Ornamental
78	*Dypsis lutescens*	Arecaceae	Puwangu	Kaattu panai	Areca palm		EX		Ornamental
79	*Hyophorbe lagenicaulis*	Arecaceae			Bottle palm	4	EX		Ornamental
80	*Livistona chinensis*	Arecaceae	Ithu gas	Thamarai panai	Fountain palm	2	EX		Medicine, landscaping
81	*Oncosperma fasciculatum*	Arecaceae	Katu kithul		Thorny palm	4	EN	VU	Medicine
82	*Phoenix dactylifera*	Arecaceae	Rata indi	Perichchambalam	Date palm	24	EX		Medicine, fruit edible
83	*Ptychosperma macarthurii*	Arecaceae			Macarthur palm	34	EX		Ornamental
84	*Ravenala madagascariensis*	Strelitziaceae		Visiri vazhai	Travellers palm	1	NE		Medicine, food, timber, ornamental
85	*Rhapis excelsa*	Arecaceae			Bamboo palm	2	EX		Medicine, ornamental
86	*Roystonea regia*	Arecaceae	Raja thal	Pakku panai	Royal palm	47	NE		Medicine, timber, ornamental
87	*Wodyetia bifurcata*	Arecaceae		Fox tail panai	Fox tail palm	17	EX		Ornamental
Shrub/Small tree									
88	*Bougainvillea glabra*	Nyctaginaceae	Boganvila	Kaahida poo	Paper flower	279	EX		Medicine, ornamental
89	*Caesalpinia pulcherrima*	Fabaceae	Monara mal	Mayir konrai	Paradise flower	3	NE		Medicine, ornamental
90	*Callistemon lanceolatus*	Myrtaceae	Kabanaya	Palasu	Bottle brush	18	EX		Medicine, ornamental
91	*Citrus x aurantifolia*	Rutaceae	Dehi	Eli muchchum pazham	Lime	11	NE		Medicine, food/flavour
92	*Citrus x limon*	Rutaceae	Lemon dehi	Elumichchai	Lemon	5	NE		Medicine, food/flavour
93	*Codiaeum variegatum*	Euphorbiaceae	Croton	Kurottan	Croton	201	NE		Medicine, ornamental
94	*Duranta erecta*	Verbenaceae	Durantha	Akayappu	Goldendew drop	NC	NE		Medicine, ornamental
95	*Euodia ridleyi*	Rutaceae			Evodia	26	EX		Medicine, ornamental
96	*Excoecaria cochinchinensis*	Euphorbiaceae		Chinese croton	Chinese croton	3	EX		Medicine
97	*Hibiscus rosa-sinensis*	Malvaceae	Wada mal	Nir paratthi	Shoe flower	4	NE		Medicine, ornamental
98	*Ixora coccinea*	Rubiaceae	Rathmal	Vedchi	Jungle geranium	NC	NV	LC	Medicine
99	*Ixora duffi*	Rubiaceae	Rathmal	Vedchi	Giant red ixora	NC	EX		Medicine
100	*Jatropha*	Euphorbiaceae			Spicy	2	EX		Medicine,

	pandurifolia				jatropha				ornamental
101	*Lagerstroemia indica*	Lythraceae		Pavalakkurunji	Crape murtle	2	EX		Medicine, ornamental
102	*Mussaenda philippica cv. Queen sirikit*	Rubiaceae	Mussenda		Mussenda	9	EX		Medicine, ornamental
103	*Nerium oleander*	Apocynaceae	Kaneru	Alari	Oleander	3	NE		Medicine, ornamental/shade, poisonous
104	*Phyllanthus myrtifolius*	Phyllanthaceae	Ganga werella	Mannankulam	Mousetail plant	NC	NV	VU	Medicine, ornamental
105	*Rosa x hybrida*	Rosaceae	Rosa	Rojapoo	Hybrid tea rose	7	EX		Ornamental
106	*Senna auriculata*	Fabaceae	Ranawara	Avari	Matara tea	1	NV	LC	Medicine
107	*Syzygium myrtifolium*	Myrtaceae			Red lip	76	EX		Ornamental
108	*Tabernaemontana divaricata*	Apocynaceae	Watusudda	Nandi vattai	Crepe jasmine	15	EX		Medicine
109	*Turnera ulmifolia*	Passifloraceae	Etuna		Yellow alder	10	EX		Medicine
Bamboos									
110	*Bambusa vulgaris*	Poaceae	Kaha una	Vellai mungil	Common bamboo	25	NE		Medicine, timber
111	*Bambusa vulgaris 'Vittata'*	Poaceae	Kaha una	Mullai mungil	Painted bamboo	2	EX		Ornamental
112	*Dendrocalamus giganteus*	Poaceae	Yodha una		Giant bamboo	5	NE		Construction scaffold, ornamental
113	*Phyllostachys nigra*	Poaceae		Karung mungil	Black bamboo	5	EX		Medicine, ornamental
Climbers									
114	*Allamanda blanchetii*	Apocynaceae			Purple Allamanda	2	EX		Medicine, ornamental
115	*Allamanda cathartica*	Apocynaceae	Wel rukaththana	Aahamandhaa	Allamanda	2	NE		Medicine, ornamental
116	*Combretum constrictum*	Combretaceae		Mulmullai	Thailand powder puff	19	EX		Medicine, ornamental
117	*Ficus pumila*	Moraceae	Thaappa wel	Kodi atti	Creeping fig	3	EX		Medicine, ornamental
118	*Scindapsus aureus*	Araceae	Pota wel		Devil's ivy	22	EX		Ornamental
119	*Thunbergia erecta*	Acanthaceae	Kotala		Bush clock vine	3	EX		Medicine
120	*Tristellateia australasiae*	Malpighiaceae			Australian gold vine	21	EX		Ornamental
Other plants									
121	*Agave angustifolia*	Asparagaceae	Kasata gaha	Kathaalai	Caribbean agave	36	EX		food, fibre, medicine
122	Canna indica	Cannaceae	Buthsarana	Kalvzhai	Indian shot	10	EX		Ornamental
123	Rhoeo spathacea	Commelinaceae	Roheo		Boat lilly	497	EX		Medicine
124	Sansevieria-trifasciata-Laurentii	Asparagaceae	Kalanda pila	Naga podhai	Mother-In-Law's Tongue	154	EX		Ornamental
125	Zephyranthes rosea	Amaryllidaceae	Minie mal	Mazhai lilly	Pink rain lilly	NC	EX		Medicine

Note: 1. NC: Not counted due to the number of plants is too high.
2. EN: Endemic; EX: Exotic; NE: Naturalized exotic and NV: Native
3. LC; Least concerned; NT: Nearly threaned and VU: Vulnerable

Conclusion

The landscaping activities in the site could be made more biocentric by including more native plants particularly endemics, threatened and vulnerable species into the landscaping activities making it a centre of awareness on biodiversity and conservation to the university community, school children and the general public in the region while serving the anthropocentric motives of urban landscaping.

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Effects of Mn concentration on the performance of ZnO thin film humidity sensor

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Abstract

ZnO is considered one of the most promising semiconductors for use as a sensing material due to its superior electrical properties, wide band gap, and high surface-to-volume ratio. Due to their enhanced sensitivity, stability, and cost effectiveness, recently there has been much interest in using ZnO thin films as humidity sensors. In this work, successful growth of Mn-doped ZnO thin films on FTO glass substrates via the spin coating process was demonstrated. Effects of different doping percentages of manganese (0%, 2%, 4%, 6%, and 8%) on properties of ZnO thin films have been investigated. A precursor solution was prepared using zinc acetate and manganese acetate, ensuring uniform mixing for controlled doping. The prepared films were deposited using a repeated spin coating process followed by annealing at 400 °C to improve crystallinity and film quality. Morphology, optical and electrical properties of the films were studied, along with the sensing properties at various levels of relative humidity. It was found that the electrical resistances of all the films decreased with increased humidity due to adsorption of water molecules on the surface resulting in better charge transport in the film. Among all the films investigated, 4% Mn-doped film showed superior performance as it had maximum sensitivity, response time, recovery time, and good electrical conductivity compared to other films. From the I-V measurement, it was found that the 4% Mn-doped ZnO film had higher current response than the other films. Optical studies show that the optimized film had a band gap value of 3.22 eV. In general, it can be concluded that 4% Mn-doped ZnO thin films fabricated using the spin-coating technique are very promising candidates for humidity sensing applications.

Keywords: Humidity sensor, Spin coating, Sensitivity, Response time, Recovery Time

Introduction

Humidity is one of the most important environmental parameters, which plays an important role in many physical, chemical, and biological processes in many fields such as agriculture, healthcare, food storage, and industrial manufacturing. Accurate humidity monitoring is critical for maintaining product quality, ensuring process efficiency, and preventing equipment damage. Excessive humidity can cause corrosion of metal components, damage of electronic devices, and promotion of microbial growth, whereas low humidity can cause material drying and malfunction of sensitive equipment [1, 2]. Humidity sensors have become an important tool for environmental monitoring and control. They are used in agriculture crop optimization, healthcare equipment, pharmaceutical storage, and industrial manufacturing processes [2, 3].

Various materials have been investigated for humidity sensing applications, including polymers, ceramics and semiconductor metal oxides. Among them, metal oxide semiconductors are preferred due to their superior sensitivity, chemical stability, low cost of fabrication and compatibility with miniaturization technologies. The electrical properties of water molecules are

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significantly affected on the surface of materials such as Zinc oxide (ZnO), tin oxide (SnO_2) and titanium dioxide (TiO_2) which makes them ideal for accurate humidity sensing [3]. ZnO is a popular n-type semiconductor with a large band gap (~ 3.3 eV), high electron mobility and excellent chemical and thermal stability. Its inherent defects such as oxygen vacancies and zinc interstitials enhance the adsorption of water molecule on the surface of the material [4]. The interaction of water molecules with ZnO causes measurable changes in electrical conductivity and thus ZnO is suitable for humidity sensing applications. ZnO is non-toxic, environment friendly and cheap with compatibility of simple techniques of fabrication such as spin coating [5].

However, pure ZnO has some limitations such as moderate sensitivity, relatively slow response and recovery time, and limited electrical conductivity. These limitations demand modification strategies such as doping to enhance the sensing properties of ZnO [6]. Doping is the deliberate addition of impurity atoms to a semiconductor lattice in order to modify and improve its characteristics. Doping enhances electrical conductivity by increasing the concentration of charge carriers and generating defect sites and oxygen vacancies, which act as active adsorption centers for target molecules [7, 8]. Transition metal doping with elements such as manganese (Mn), Cobalt (Co) and Nickel (Ni) alters the electronic structure, increases the electrical conductivity and boosts the charge carrier mobility, creating more active sites for water molecule adsorption [9].

Manganese (Mn) is a good dopant for ZnO because its ionic radius is close to that of zinc ions (Zn^{2+}), so it can be substituted easily without much distortion in the structure. Mn doping leads to the increase of the concentration of oxygen vacancies and the formation of new defect sites that are beneficial for the adsorption of water molecules on the surface of ZnO. The Mn-doped ZnO thin films have better electrical conductivity and humidity sensing performance than the pure ZnO due to the increase in surface roughness and the formation of more active sites [10]. The humidity sensing performance is greatly affected by the concentration of the Mn dopant. The optimal concentration enhances the number of active surface sites and the mobility of charge carriers. However, high doping levels result in the formation of defects and secondary phases that reduce the electrical conductivity and hinder charge transfer [10]. The importance of optimizing the dopant concentrations for the sensing performance has been pointed out recently [11, 12].

ZnO is a well-studied material for humidity sensing. Farahani et al. showed that electrical resistance of ZnO changed dramatically with relative humidity [10]. Chen and Lu reported that the sensitivity was improved due to the high surface-to-volume ratio of ZnO nanostructures [3]. Numerous researchers have examined the sensing capabilities of ZnO doped with transition metals, and Mn-doped ZnO has drawn a lot of interest because of the appropriate ionic radius of Mn ions. Due to an increase in oxygen vacancies and defect sites, Mn-doped ZnO thin films were shown to be more sensitive than pure ZnO [1]. Similarly, Zhang et al. [12] reported that moderate Mn concentrations improved the charge carrier transport and adsorption behavior considerably. The humidity sensing mechanism is related to the chemisorption of water molecules at low humidity levels, forming hydroxyl groups, and physisorption and multilayer formation at high humidity levels, enabling proton transport through the Grotthuss mechanism, and resulting in enhanced conductivity [13, 14]. Many studies have been done on ZnO based humidity sensors but the changes in fabrication processes, dopant concentrations and sensing

conditions affect the performance of the sensors. Few studies have been done on spin-coated Mn-doped ZnO thin films under low-cost laboratory conditions.

The present study focuses on preparing Mn-doped ZnO thin films on FTO-coated glass substrates through the sol-gel spin coating technique. It investigates how the structural, optical, electrical, and humidity sensing characteristics are affected by different Mn doping concentrations (0%, 2%, 4%, 6%, and 8%). It also studies the humidity sensing performance in terms of sensitivity, response time, recovery time and electrical conductivity to find the optimal Mn doping concentration for enhanced humidity sensing performance.

Materials and Methodology

Materials

Analytical grade chemicals were used as received. The Zn precursor was zinc acetate dihydrate ($Zn(CH_3COO)_2 \bullet 2H_2O$, 99.9% purity) and the dopant source was manganese acetate tetrahydrate ($Mn(CH_3COO)_2 \bullet 4H_2O$, 99.9% purity). Ethanol (99.9% purity) was used as the solvent and acetylacetone was used as the stabilizer to improve the homogeneity of the solution.

Preparing the Substrate

FTO-coated glass substrates were cut into 2 cm x 1 cm pieces. The substrates were cleaned in an ultrasonic bath sequentially with acetone, ethanol and distilled water for 10 min each time. The middle conducting region was selectively removed by zinc powder and HCl to define the sensing area, which was checked by a multimeter. Substrates were re-cleaned and dried after etching.

Preparation of Precursor Solution

Zinc acetate dihydrate (0.1 M) was dissolved in ethanol and then manganese acetate tetrahydrate was added according to the required doping concentrations (0%, 2%, 4%, 6% and 8% according to zinc content). The solution was stirred at room temperature for 30 min to ensure complete dissolution. Acetylacetone (stabilizer) was added dropwise to control the hydrolysis and prevent precipitation. The solution was stirred until a clear homogeneous mixture was obtained and stored in a closed container.

Thin-film Deposition

Mn-doped ZnO thin films were deposited by a two-step spin coating process. About 0.1 mL of precursor solution was dropped on the substrate and spin coated at 500 rpm for 5 seconds (spreading step) and then at 2000 rpm for 30 seconds (uniform film formation). After each coating cycle, samples were dried on a hot plate at 100 °C for 10 minutes. The procedure was repeated for 5 cycles to obtain the desired film thickness.

Annealing

The coated films were annealed at 400 °C for 1.5 h in the box furnace with the heating rate of 5 °C/min. This annealing step improved crystallinity, removed organic residues and improved film stability and adhesion.

Creation of humidity environment and humidity sensing measurements

Saturated salt solutions were used to provide controlled relative humidity environments. Solution of magnesium chloride ($MgCl_2$) was used for ~33% RH, sodium chloride (NaCl) for 75% RH and potassium chloride (KCl) for 85% RH. The fabricated samples were placed in sealed containers near the saturated salt solution to expose them to the humid environment without direct contact with the liquid.

Measuring Resistance

The electrical resistance of Mn-doped ZnO thin films was measured by using a digital multimeter under different RH conditions. Electrical contacts were made by connecting conducting wires to the exposed FTO regions on either side of the deposited film using crocodile clips. The resistance values were measured after the time taken for stabilization at each humidity level.

Response and Recovery Time

Response time was defined as the time taken for the sensor to reach 90% of the total resistance change when exposed to a higher humidity environment. The recovery time was defined as the time needed for the sensor to achieve 90% of its initial resistance value when taken out of the humid atmosphere. These measurements were performed by continuously monitoring the resistance change by switching at different humidity levels.

Current-Voltage (I-V) Measurements

I-V measurements were performed by applying a DC voltage across the Mn-doped ZnO thin film and measuring the current using a digital multimeter. Measurements were performed under high relative humidity conditions (~85% RH) to enhance charge transport and to enable accurate current measurement.

Computation of Sensitivity

Sensitivity (S) was calculated from the resistance values measured in different RH conditions:

$$S = \frac{R_{low\ RH} - R_{high\ RH}}{R_{low\ RH}}$$

where R_{low} and R_{high} represent the resistance values at low and high relative humidity levels, respectively.

The reduction of resistance at high humidity is due to the adsorption of water molecules which improves ionic conduction.

UV-Vis Spectroscopy

The prepared thin films were investigated by UV-Vis spectroscopy for their optical properties. The absorbance spectra of all samples were recorded in the wavelength range of 300-700 nm using spectrophotometer with bare FTO/glass substrate as the reference.

FTIR Spectrum

Fourier Transform Infrared (FTIR) spectroscopy was used to confirm Zn-O bond formation and identify functional groups. Spectra were taken in the 400-4000 cm^{-1} range at room temperature.

Results and Discussion

Sensitivity Analysis

The sensitivity of the Mn-doped ZnO thin films was calculated from the low and high humidity resistance change. Figure 1 shows the change in sensitivity with Mn doping concentration.

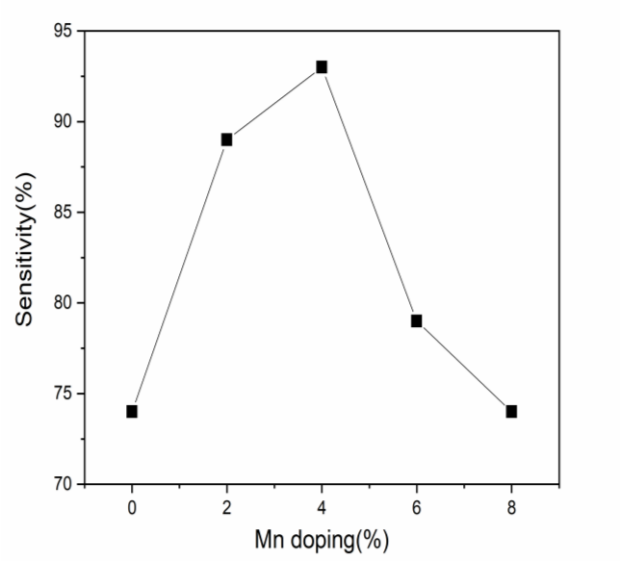


Figure 1: Variation of sensitivity of Mn-doped ZnO thin films.

The undoped ZnO thin film exhibited sensitivity of ~73%, which is relatively low compared to the doped samples due to limited active adsorption sites on the surface. The sensing performance increased considerably by the addition of Mn to the ZnO lattice. This improvement can be ascribed to the increase of oxygen vacancies and defect sites induced by Mn doping. These defects could serve as active centers for adsorption of water molecules and therefore improve the interaction between sensing material and surrounding humid environment [1,5].

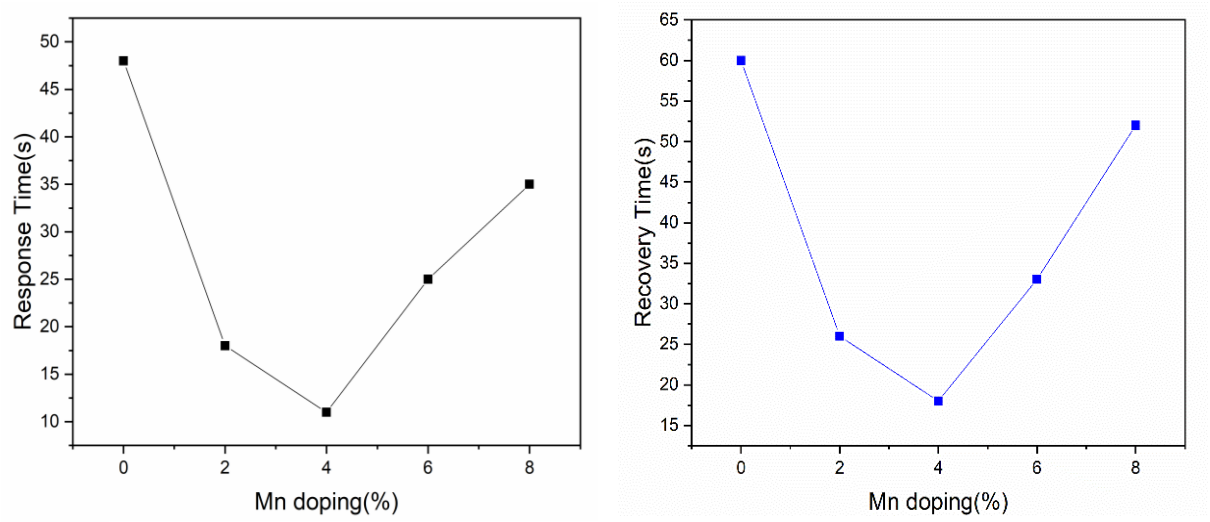
Among all the investigated samples, the 4% Mn-doped ZnO thin film exhibited the highest sensitivity of ~93%. This shows that 4% Mn is the best concentration for humidity sensing applications. The trade-off between defect generation and electrical conductivity at this doping level is favorable for efficient adsorption and charge transport. The larger number of adsorbed water molecules facilitates the proton conduction on the film surface resulting in a large reduction of the resistance under humid conditions [3].

The 2% Mn-doped sample sensitivity was ~89% and the 6% Mn-doped and 8% Mn-doped samples were ~78% and ~73% respectively. The reduced sensitivity at higher Mn concentrations (6% and 8%) can be attributed to the over-insertion of Mn which leads to defect clustering and structural distortion in the ZnO lattice. These effects can decrease the mobility of charge carriers and limit the effective adsorption of water molecules on the surface of the film. Hence, the sensing response is less pronounced than for the optimally doped sample [1, 4].

Response and Recovery Time

The response and recovery times are important parameters that determine the practical applicability of humidity sensors. Response time is the time taken by the sensor to reach a value close to 90% of the final resistance when exposed to humidity. Recovery time is the time taken to return to its original state after removing humidity [15].

As shown figure 2, the results reveal that the response and recovery times decreased significantly with the Mn doping up to 4%. The ZnO thin film doped with 4% Mn showed the shortest response time (~10 s) and recovery time (~15 s), implying fast adsorption and desorption of water molecules. This behavior is attributed to the increase in the number of active adsorption sites and the improvement of charge transport pathways induced by Mn doping [16].



(a) (b)

Figure 2: Response time (a) and recovery time (b) of Mn-doped ZnO thin films.

The fast response of the 4% sample demonstrates an effective interaction of water molecules with the sensor surface. A short recovery time also indicates the ability to quickly desorb water molecules when the humidity drops. These features are highly desirable for real time monitoring applications where rapid detection and recovery is required.

At higher Mn concentration, the response and recovery times were increased. This can be related to excessive defect formation and decreased carrier mobility which can slow down adsorption and desorption processes. Thus the 4% Mn-doped ZnO thin film exhibited the best dynamic sensing performance among the studied samples.

Current–Voltage (I–V) Characteristics

The electrical behavior and charge transport properties of the fabricated Mn-doped ZnO thin films were investigated by measuring their current–voltage (I–V) characteristics under high humidity conditions. The I-V characteristics are presented in figure 3.

For all doping concentrations, the measured I-V curves exhibited an almost linear relationship between the current and the applied voltage. The linear behavior implies an ohmic conduction, meaning that the electrical contacts between the FTO electrodes and the sensing layer were stable and no significant barrier existed at the interface [5].

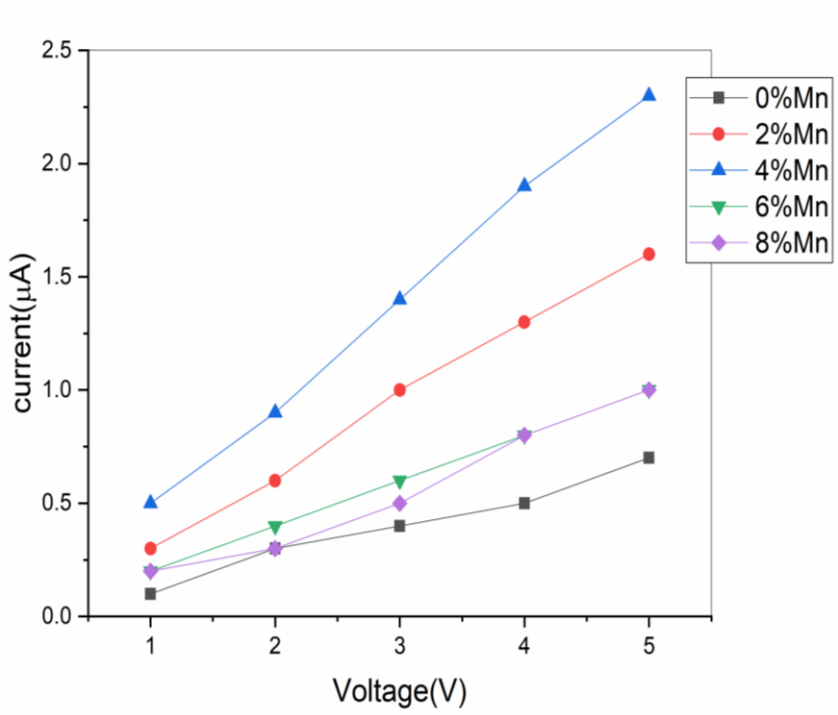


Figure 3: I-V characteristics of Mn-doped ZnO thin films at 85 % RH

The undoped ZnO sample presented relatively low current values attributed to its limited charge carrier concentration and fewer active adsorption sites. The addition of Mn resulted in a significant increase in current, indicating improved conductivity. The incorporation of Mn ions into the ZnO lattice generated more defect states and oxygen vacancies, which increased the generation and transport of charge carriers. These defects also acted as adsorption sites for water molecules, further enhancing the conductivity.

Among all the samples studied, the 4% Mn-doped ZnO thin film registered the highest current values throughout the voltage range. This result shows that the doping concentration of 4% Mn provides an optimal doping concentration for charge transport and humidity sensing applications. At this concentration the balance between oxygen vacancy formation, carrier concentration and lattice stability seems to be the most favorable. The highest sensitivity and shortest response and recovery times observed for the 4% sample are consistent with the increased conductivity observed.

The higher current in the 4% Mn-doped sample can also be attributed to increased proton conduction under humid conditions. The adsorbed water molecules dissociate to form hydronium ions, which are involved in charge transport via the Grotthuss proton hopping mechanism [17]. This process is favoured by the higher availability of active adsorption sites in the optimally doped sample which results in improved electrical response [5].

When the concentration of Mn was increased beyond 4%, a decrease in current was observed. This reduction may be associated with the excessive defect formation, defect clustering and possible structural distortion in the ZnO lattice. Too many defects can act as traps for carriers. This reduces the mobility of charges and prevents efficient charge transport. Moreover, high concentrations of Mn may reduce the effective surface area for water adsorption and thus the proton conduction.

Study of Optical Absorption

Optical properties of prepared Mn-doped ZnO thin films were studied by UV-Visible absorption spectroscopy. The UV-Visible absorption spectrum of the 4% Mn-doped ZnO thin film is shown in figure 4.

The absorption spectrum exhibits a strong absorption in the ultraviolet region and a relatively low absorption in the visible region, which is the characteristic feature of ZnO semiconductors. This behavior is mainly due to the wide band gap nature of ZnO. The high absorption in the ultraviolet region is due to the transitions of electrons from the valence band to the conduction band. As the energy of the photon approaches the energy of the band gap, a sharp rise in absorption is generated, which gives rise to the absorption edge in the spectrum.

An absorption edge was observed at about 385 nm. The optical band gap energy was estimated from the absorption edge wavelength using the relation:

$$E = \frac{hc}{\lambda}$$

where E is the band gap energy, h is Planck's constant, c is the speed of light and λ is the absorption edge wavelength [5,6].

The optical band gap energy of the 4% Mn-doped ZnO thin film was calculated to be about 3.22 eV using the observed value of the absorption edge. This value is slightly lower than the usual band gap of pure ZnO, which is usually reported to be around 3.30 eV. The observed decrease in band gap energy indicates modification of electronic structure of ZnO by incorporation of Mn.

This decrease in band gap energy may be attributed to the contribution of impurity levels and localized defect states in the forbidden energy gap. The incorporation of Mn ions into the lattice of ZnO may lead to the creation of extra electronic levels in the vicinity of the conduction or valence bands. These defect states lower the energy required for electronic excitation and thus lower the optical band gap. This decrease of the band gap is also associated with the formation of oxygen vacancies related to the incorporation of Mn [11].

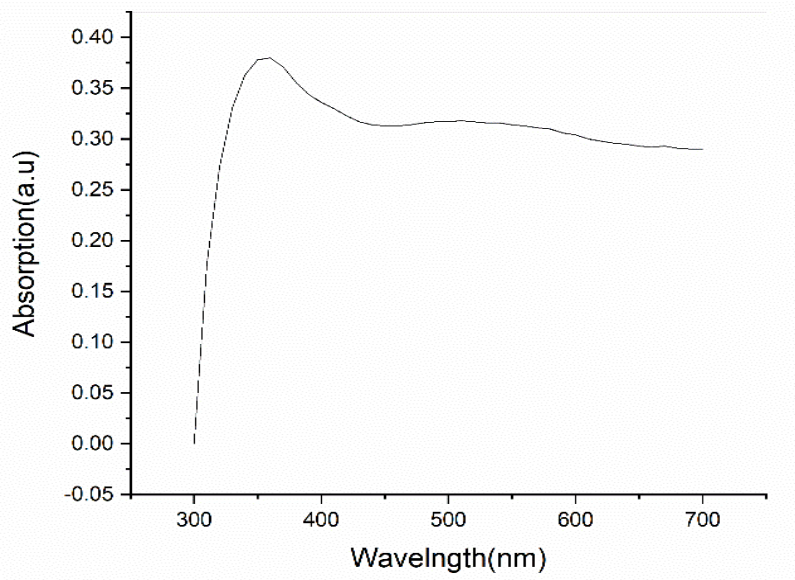


Figure 4: UV-Visible absorption spectrum of 4 % Mn-doped ZnO thin film

FTIR Spectroscopic Studies

Fourier Transform Infrared (FTIR) spectroscopy was used to study the chemical bonding, functional groups and molecular interactions in the fabricated Mn-doped ZnO thin films. Figure 5 shows the FTIR spectrum of 4% Mn-doped ZnO thin film.

Several distinctive absorption bands that corresponded to various vibrational modes were visible in the FTIR spectra of the 4% Mn-doped ZnO thin film. The broad absorption band observed around 3200-3600 cm^{-1} is attributed to O-H stretching vibrations. The broad peak indicates the presence of the hydroxyl groups and physically adsorbed water molecules on the surface of the thin film. The hydroxyl groups play a very important role in humidity sensing applications as they provide active sites for the adsorption of water molecules. The presence of these hydroxyl-rich surfaces enhances the proton conduction by the adsorption of water molecules and contributes greatly to the sensing mechanism [3, 18].

Another absorption peak which appears near 1600 cm^{-1} can be assigned to the bending vibration of H-O-H molecules. This peak further confirms the presence of adsorbed moisture on the ZnO thin film surface. Adsorbed water molecules are beneficial for humidity sensing as they can facilitate charge transport through proton hopping mechanisms. The O-H stretching and H-O-H bending vibrations indicate that the surface of the film has a high affinity for water adsorption, which is important for high humidity sensitivity [3].

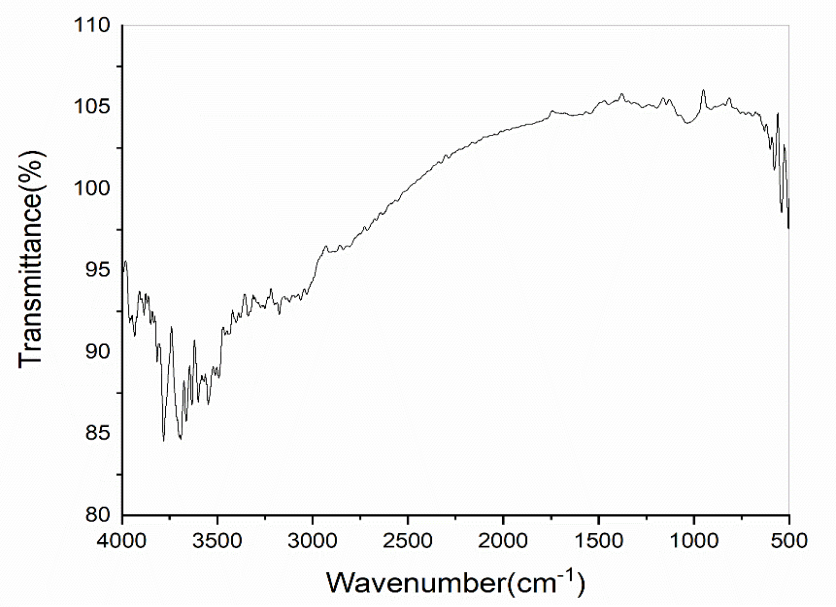


Figure 5: FTIR spectrum of 4% Mn-doped ZnO thin film

The absorption band in the low wavenumber region (ca. 500-600 cm^{-1}) was assigned to the Zn-O stretching vibrations. One of the important features of FTIR spectra is the presence of this peak which confirms the successful formation of ZnO in the fabricated thin films. The desired ZnO crystal structure has been successfully formed through the spin coating and annealing process as evidenced by the presence of the characteristic Zn-O absorption band [5].

The observed FTIR peaks suggest that the Mn-doped ZnO thin films fabricated contain structural Zn-O bonds and surface hydroxyl groups. Both these properties are directly related to the humidity sensing performance. The Zn-O network provides the semiconducting framework for

charge transport and the hydroxyl groups assist in the adsorption of water molecules and contribute to the electrical conductivity changes during sensing.

Conclusion

Mn doped ZnO thin films were fabricated on FTO glass substrates using sol-gel spin coating technique and humidity sensors were evaluated. All the films showed a decrease in electrical resistance with increasing relative humidity due to adsorption of water molecules. The 4% Mn-doped ZnO thin film showed the highest sensitivity, fastest response time and fastest recovery time compared to other investigated samples (0%, 2%, 4%, 6% and 8%). The current–voltage (I–V) characteristics showed ohmic behavior and highest current response was observed for 4% Mn-doped sample. Optical characterization shows a band gap of 3.22 eV which is less than the normal value of 3.3 eV for ZnO due to the presence of Mn. FTIR analysis confirmed the Zn-O bonding and presence of hydroxyl groups required for humidity sensing. The performance degraded with increasing Mn contents (6 and 8%) due to defect clustering and lattice distortion. Therefore, the spin coated 4% Mn-doped ZnO thin films are promising candidates for low-cost and high-performance humidity sensors for practical monitoring applications in agriculture, healthcare, food storage, and industrial process control.

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