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Valorization of Typha domingensis Pers. fibers for Sustainable Mustard Microgreen Cultivation

C. Naveena Shri[1,2], S. Amsamani[1]*

[1]*Department of Textiles and Clothing, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore*
[2]*Department of Costume Design and Fashion, KPR College of Arts, Science and Research, Coimbatore*

Abstract:

Invasive aquatic species, often seen as a burden, can actually offer surprising benefits as renewable resources in sustainable agriculture. The research focuses on Typha domingensis pers, which has been largely overlooked in agricultural innovations. The aim of the study is to explore its potential by transforming its fibers into needle-punched nonwoven mats for the environmentally friendly cultivation of mustard microgreens.

Typha mats were made by needle punching technique and incorporated natural elements such as aloe vera and NPK (Nitrogen, Phosphorus, Potassium) coatings to promote plant growth and enhance the nutritional profile of the microgreens. To assess their effectiveness, the performance of our innovative Typha mats was compared with that of untreated mats, commercial coir mats, and standard tissue paper substrates. Physical evaluations were conducted to measure the strength, stiffness, and moisture management of the mats.

The Typha mats demonstrated adequate strength and effective moisture management, proving their viability as cultivation substrates. Notably, the untreated Typha mats outperformed all other substrates, yielding an impressive 13.13 grams of microgreens per tray. This represented a 119.6% higher yield than the tissue paper control (5.98g) and a 217.9% higher yield than the commercial coir mat (4.13 g). Additionally, the NPK-treated mats showed a significant increase in bioactive compounds, with heightened levels of total phenolic content, chlorophyll, and β-carotene. Interestingly, sensory evaluations indicated that the quality and acceptability of microgreens grown on all types of mats were similar, meaning the innovative mats did not compromise taste or quality. No statistically significant differences were observed in the sensory values of the microgreens ($p > 0.05$).

This research underscores the potential of biomass-derived nonwoven substrates as sustainable alternatives to traditional growing media in agriculture. By utilizing these biodegradable materials, advanced circular bioeconomy initiatives can be met, reduce human dependence on non-renewable inputs, and inspire innovation in urban and controlled-environment agricultural practices. Together, these efforts contribute to a more sustainable and greener future.

Keywords: *Agro- textiles, biodegradable grow mats, microgreens cultivation, needle-punched nonwovens, Typha domengensis Pers. fibers*

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1. Introduction

In light of the growing energy demand and heightened environmental concerns, scientists and researchers have undertaken initiatives to enhance processes and materials that serve as sustainable energy solutions, as well as eco-friendly options [1]. Among the innovative approaches being explored, invasive plant biomass has emerged as a promising source for various applications, including bio-fertilizers, biochar, and bio-composites. The potential use of this biomass can significantly reduce the carbon footprint by providing sustainable resources [2]. For instance, the invasive plant biomass, such as Typha domengensis Pers, grows rapidly, often overwhelming entire aquatic ecosystems and hindering the ecological balance [3]. This research is focused on extracting fibers from Typha domengensis Pers.Pers and transforming them into non-woven mats through a needle punching process. This innovative approach is aimed at creating bio mats specifically designed for microgreens cultivation. Furthermore, the increasing population, urbanization, and climate change have led to a notable decline in arable land. As agricultural land becomes scarcer, the challenge of ensuring food sustainability to meet the nutrient needs of a projected global population of 9.7 billion by 2050 becomes increasingly daunting[4]. This situation, characterized by a reduction in farmland and an increase in micronutrient deficiency, calls for the adoption of urban farming as a viable solution. Urban farming leverages technology and automation to optimize land use while addressing nutritional needs, effectively emerging as a response to the intertwined issues of land scarcity and food insecurity. This strategy not only aims to boost productivity but also seeks to minimize

****Corresponding Author :***
Dr. B. Senthil Kumar
Email: dr.amsamani@gmail.com, naveenaarun04@gmail.com

environmental impacts through the use of climate-controlled high-rise buildings. These innovations offer numerous advantages, including enhanced biosecurity, pest freedom, and reduced transportation needs for fresh produce [5]. Ultimately, this research endeavours to tackle the dual issues of providing fresh foods to urban communities in a sustainable manner while simultaneously converting invasive green biomass into a practical and eco-friendly solution as grow mats. Natural fibers such as jute, hemp, coir, and kenaf have been explored for sustainable fiber-based materials; however, their application as growing substrates for microgreens remains limited. Similarly, the potential of Typha domengensis Pers.as a needle-punched nonwoven growing medium has received limited attention, creating a research gap in its valorization for sustainable microgreen cultivation.

This study presents a novel interdisciplinary approach combining textile engineering and sustainable agriculture. The key contributions include: (i) the first reported application of Typha domengensis Pers.needle-punched nonwoven mats for microgreens cultivation, (ii) development of a mechanical fiber extraction me thod to enhance sustainability, (iii) functionalization of grow mats using aloe vera and NPK coatings to improve nutritional quality, and (iv) evaluation of physical, agronomic, and sensory properties to assess substrate performance. This research demonstrates a circular bio-economy pathway for converting invasive biomass into value-added agricultural substrates.

2. Methodology

2.1 Development of non-woven mats from Typha domengensis Pers. fibers

Typha domengensis Pers, an invasive aquatic plant, grows extensively and occupies puddles, negatively impacting the aquatic ecosystem [6]. Typically, this plant is removed by burning when the water in a pond or puddle recedes. Its growth disrupts development and causes imbalances in the ecosystem [7]. Typha domengensis Pers. contains fibrous materials that are similar to those found in jute and other unconventional fibers, and mostly finds application as reinforcement in composites [8].

Several methods for fiber extraction were tested. Water retting was not feasible due to its aquatic nature, and chemical retting raised sustainability concerns. Therefore, a new mechanical method of fiber extraction was developed, addressing the issues associated with the other two methods. The process for preparing Typha fibers initially involves cleaning and sun-drying. The leaves are then cut to 10 cm and boiled for three hours. After boiling, they are blended for 15 seconds to create a fibrous slurry, from which water is squeezed out to obtain the fibers, which are later dried in sunlight (28 °C to 30 °C)for a period of two days [9].

As a pilot study, the extracted Typha fiber is blended with jute into non-woven fabrics of various combinations. These blends are made into non-woven needle-punched mats and tested for their basic physical properties [10]. The combination that exhibited the best physical properties was identified as the combination of 70% Typha and 30% Jute and was selected for further study. The needle-punching process was carried out at a needle density of 180 punches/cm², a penetration depth of 8 mm, a fabric density of 3.290 g, and a production speed of 600 strokes/min. These processing parameters were maintained consistently during the fabrication of the selected non-woven mats to ensure uniform fabric structure and reproducibility.

2.2 Value Added Finishing

The optimum fiber combination that performed well was selected based on the test results. As the developed mats are for growing mustard microgreens, a value-added finish was applied using aloe vera gel and an NPK solution.

2.2.1 NPK coating

For the study, commercially available NPK solution, Erwon® NPK 20:20:20 Liquid Growth Fertilizer was used. Five different concentrations of the liquid NPK solution 2 ml, 4 ml, 6 ml, 8 ml, and 10 ml of the fertilizer were mixed with 500 ml of tap water.

Five pieces of the developed non-woven mat (NP4) that performed well in the physical tests was cut to dimensions of 190 mm x 130 mm to fit the microgreens tray. These samples were soaked in the various diluted NPK solutions for 10 minutes. After soaking, the samples were removed, squeezed out, and dried at 70^0 C for 24 hrs [11].

2.2.2 Aloe vera gel coating

Similarly, Aloe vera gel was extracted from a fresh aloe vera plant and ground into gel. The gel measuring 2ml, 4ml, 6ml, 8ml, and 10ml was mixed with 500ml of tap water. Five pieces of the developed non-woven mat were cut to the dimensions of 190mm X 130mm to fit the microgreens tray. The samples were soaked in the diluted aloe vera gel solution for 10 minutes, after which the samples were removed, squeezed out, and dried at 70^0 C for 24 hrs [11].

2.3 Optimization of value-added finish- Germination study

In order to optimize the coating concentrations, a germination study was done. The coated samples were weighed, crushed, and mixed with distilled water 5 times the weight of the coated samples (1:5). The content was placed in a shaker incubator for 1 h. The mixed solution is filtered using Waltman filter paper. Two discs of Waltman filter paper are placed on a petri dish, and about 10 undamaged healthy mustard seeds are placed on the filter paper in the petri dish. 4ml of the filtered saturated solution is poured onto the petri dish at room temperature for 7 days. Care was taken to see that the petri-dish was not exposed to direct sunlight. Triplicates were made for each variation, and the Seed germination percentage and relative seed germination percentage were calculated using the following formula [12]. The primary roots that reached a minimum of 5mm were

considered to have germinated [13]. The sample with a high percentage of germination was selected for further study.

$$Seed\ germination(\%) = \frac{No.\ of\ germinated\ seeds}{No.\ of\ tital\ seeds} X\ 100\ ....(Equation\ 1)$$

$$Relative\ Seed\ germination(\%) = \frac{No.\ of\ germinated\ seeds(samples)}{No.\ of\ tital\ seeds\ (control)} X\ 100\ ...(Equation\ 2)$$

2.4 Physical Testing of the developed and commercial non-woven mats

The developed non-woven Typha mat with the optimized value-added finished mats is tested for its physical properties. The names of the samples taken for the study are depicted in Table 1.

Table 1 - Sample Nomenclature

Samples	Content
T1	Tissue paper (Control)
T2	Needle-punched Typha fiber mats
T3	Aloe vera-treated needle-punched Typha mat
T4	NPK-treated needle-punched Typha mat
T5	Commercial coir mat

2.4.1 GSM

A GSM cutter was used to cut the fabric using rotating blades, typically 100cm2 in a circular motion. The cut sample is then weighed on an electronic balance. A total of 10 random samples were taken, and the values are consolidated [14].

2.4.2 Tensile Strength

The tensile index indicates the maximum force required to break a standard-width test strip and is measured in megapascals (Mpa). The samples were evaluated for tensile index and elongation in accordance with ASTM D828-97. A constant-rate-of-elongation tensile testing machine was used for the assessment. The test specimens, which measured 2.54 ±0.5 cm in width and 25.4 ±0.5 cm in length and were free of creases, holes, or wrinkles, were held securely between the machine's jaws. A total of ten specimens in each principal direction were tested, and both tensile strength and elongation were recorded.

2.4.3 Stiffness

Stiffness serves as a crucial factor for assessing the rigidity and bending strength of a material. To measure the stiffness, the Shirley stiffness tester was utilized. Samples of needle-punched fabric were cut to match the dimensions of the template (15cm x 2.5cm). The prepared sample was placed under the template, and both were positioned on the tester's platform. The template is then gradually moved until the sample bends and aligns with the index line visible in the mirror. This process was repeated for all four sides. Ten repetitions for each variation were conducted to calculate the average stiffness value.

2.4.4 Thickness

A thickness gauge was employed to determine the thickness of the needle-punched non-woven fabrics, following the ASTM D 5729 - 97 method. The gauge comprises a base component known as an anvil and a presser foot that applies a specific pressure to the sample. The thickness of the material is measured as the distance between the anvil and the presser foot. A load of 5 kPa was applied to the gauge, and thickness readings were taken at ten different locations across the fabric. The average value obtained indicates the thickness of the mat.

2.4.5 Sinking

Following the AATCC Test Method 17-1994, the sinking test was performed. The Typha needle-punched fabrics were cut to dimensions of 25mm by 25mm. A 1000 ml beaker was filled with deionized water, into which each sample was carefully dropped. The stopwatch was activated as soon as the fabric made contact with the water's surface, and the duration taken for the nonwoven to sink to the bottom of the beaker was recorded as the sinking time of the nonwoven mat. This procedure was repeated for the additional samples, and the average value was determined.

2.4.6 Wicking

A wicking test was performed to determine the moisture absorption capability of the non-woven fabrics. For each variant, 10 samples measuring 15 cm in length and 5 cm in width were cut. One end of each sample was connected to a 2g weight and positioned on a wooden block. The other end, which was immersed in a tray of distilled water for 2 cm, was observed for water rise. The height of the water above the immersed portion was recorded after maintaining a constant time of 1 minute. This procedure was repeated for the remaining replicas, and the average value was calculated.

2.4.7 Moisture content

A sample dimension of 2 inches by 2 inches was cut to assess the moisture properties of the samples. For each variety, ten replications were made. The initial weight of every sample is recorded and placed in a hot air oven set at 105°C for 1.5 hours. After that duration, the samples are removed and weighed. The percentage of moisture content is determined using the following equation.

$$Moisture\ Content = \frac{A - B}{A} X\ 100\ .....Equation\ 3$$

A – Original weight of the sample (in grams)

B – Oven dry mass of the sample (in grams)

2.5 Plant culture study

2.5.1 Plant Culture Conditions and Growing Medium

The three developed non-woven mats were evaluated alongside commercial coir and tissue paper by growing mustard microgreens. The seeds were from the brand “allthatgrows”. In August 2025, mustard microgreens, scientifically known as Brassica juncea [15], were cultivated in a shade net conditions for optimal growth. Each sample was subjected to four replicates to ensure the reliability of the results. The microgreens grown on tissue paper, commonly

used by urban populations for microgreen cultivation, served as the control group.

2.5.2 Growing Conditions

The sowings were carried out in a completely randomized manner across a total of 18 trays, with six treatments and three replications. The seeds for each tray were measured and placed randomly, ensuring that all seeds in each tray were of equal measure. The mats of all varieties were set on recycled polyethylene terephthalate (R-PET) trays, which have an area of 126 cm^2 and a weight of 6 grams. Each tray had eight holes at the bottom to allow for excess water drainage. For control trays, tissue papers were used.

The mats were pressed gently to achieve a uniform surface area before being watered. Approximately 2.5 grams of mustard seeds were sown in each tray, after which the mats were watered again, and the trays were covered with food-grade wraps to aid germination.

Once the microgreens had sprouted, the protective cover was removed, and they were placed under shade nets. The temperature inside the shade net was between 21.6^0 C to 24.4^0 C and the relative humidity was between 50% to 90% during the time of the study. Watering was conducted once a day at 9:00 AM, lasting for 10 minutes. A measured amount of water, approximately 100 ml, was sprayed onto each tray[16]. The mats and the microgreens grown on them are depicted in Fig.1.



Figure 1 - Mustard microgreens in different grow medium

2.6 Determination of Yield

For harvesting, the mats were carefully removed from the trays and placed on a flat surface. Disinfectant scissors were used to trim the microgreens, ensuring that the cuts were made just above the mats. To measure the height, the average length of the microgreens from each tray was recorded. Measurements were taken from the tip of the leaf to the shoot just above the grow mats. A total of 40 microgreens were sampled from each variation (10 from each tray), and the average value was recorded. The total weight of the microgreens from each tray was measured with 4 replications for each variation.

2.7 Sensory Evaluation

Sensory assessments were carried out for all five treatments by a group of sensory specialists. The evaluations concentrated on different characteristics, such as appearance, texture, taste, color, and flavor. Thirty sensory specialists received samples without labels and were instructed to taste them. The findings were represented using a hedonic scale, with ratings of up to 9 points. Sensory perception and acceptability ballots were given to each participant. The intensity perception of microgreens' sensory characteristics was assessed using a nine-category horizontal line scale with labels ranging from none (1) to strongest imaginable (9), while overall acceptability, along with the liking/acceptability of appearance, texture, and flavor, was measured using a nine-point hedonic scale with verbal anchor labels ranging from highly unacceptable (1) to highly acceptable (9). Line scales were deemed a suitable option for consumer sensory and acceptability assessments of microgreens, as they can be utilized for both intensity and hedonic responses.

2.8 Determination of Total Phenolic Compounds

Evaluating the total phenolic compounds is crucial for assessing a plant's ability to act as an antioxidant, which is also beneficial for human health [17]. The analysis was conducted on five distinct samples of microgreens, following the protocols outlined by [18]. Approximately 1 gram of fresh microgreens was taken and blended with 10 ml of methanol and 1% formic acid. These were then centrifuged, and the total phenolic content was quantified using the Folin-Ciocalteu method. The test values are measured as mg of gallic acid equivalent per gram of fresh weight.

2.9 Determination of Chlorophylls

The chlorophyll levels of the five microgreen samples (T1 to T5) were assessed by collecting the microgreens from their individual trays. Approximately 1g of the microgreens was collected, frozen with liquid nitrogen, then homogenized with 80% acetone at a ratio of 1:10 (w/v) and mixed for 30 minutes, after which the chlorophyll a and b were calculated using the formula outlined by [19].

2.10 Determination of Beta Carotins

In plants, β-carotene plays essential roles in photosynthesis by acting as an accessory pigment that captures light and serves as a protective agent against detrimental light. It also functions as an antioxidant to help prevent cellular damage and generates precursors for plant hormones, thus affecting growth, responses to stress, and general plant well-being[20]. Following the procedure and formula stated by [18, 21] Beta carotene values were calculated.

2.11 Statistical Analysis

For the study, the data were collected and recorded in Microsoft Excel 2021, and statistical analyses were performed using the Statistical Package for the Social

Sciences (SPSS) software. The means obtained from various tests were compared using analysis of variance (ANOVA) at a significance level of 5% ($p \leq 0.05$). The statistical differences between sample groups were assessed using a t-test, also at a significance level of 5% ($p \leq 0.05$). The 'p' value represents the probability that any observed difference between groups is due to chance. Additionally, Post hoc test was conducted to identify significant differences in the growth analysis of the microgreens.

3. Results and Discussion

3.1 Optimization study – Germination test

The results of the germination study clearly show that the optimal concentrations were 4 ml for the NPK coating and 6 ml for the aloe vera gel. These two concentrations achieved a 100% germination rate, outperforming all other tested concentrations. Therefore, these two coating concentrations were selected for further study. The results of the germination study provide clear insights into the effectiveness of different coating materials on seed germination rates. This exceptional performance indicates that these specific concentrations are particularly suitable for enhancing seed germination among the selected concentrations.

3.1.1 Physical testing of various microgreens grow mats

The physical testing results of the selected grow medium are given in Table 2. The control sample tissue paper (T1) showed very low strength, stiffness, and stability, confirming its limited use as a grow mat. Needle-punched Typha mats (T2) performed significantly better, with higher strength and stiffness due to effective fiber interlocking. Bio-treatments further improved performance. The aloe vera–treated mat (T3) showed the highest strength among Typha samples, indicating improved fiber bonding, while the NPK-treated mat (T4) also exhibited enhanced mechanical stability without increasing thickness. Typha mats exhibited a longer sinking time than the control, indicating better structural integrity in water. Their moderate wicking behaviour supports sustained moisture availability rather than rapid water loss. The commercial coir mat (T5) had the highest strength and stiffness, but its high GSM and lower wicking may restrict uniform moisture distribution. Overall, treated Typha mats, T3 and T4, offer a good balance of strength, stability, and moisture management, making them promising sustainable alternatives to commercial grow mats.

3.2 Determination of Yield

3.2.1 Weight

The harvested microgreens were weighed using a high-precision electronic balance. Each tray, which contained different growing mediums and replications, was measured individually, and the corresponding values were recorded and presented in Table 3. Statistical analysis showed significant variations among the various growing media. Sample T2 exhibited the highest harvest weight at 13.13 g, while sample T5 showed the lowest harvest weight at 4.13 g. The higher yield may be due to the untreated Typha mat lacking additional coatings, which preserved its moisture-management and structural properties. Its moderate wicking behaviour likely provided consistent moisture to the microgreens, promoting growth and biomass accumulation. In contrast, the aloe vera and NPK coatings altered the mats' physical characteristics, affecting moisture distribution and yield. This indicates that the typha-grown mats, without any treatments, provided an optimum environment for mustard microgreen cultivation.

Table 3 - Weight of the mustard microgreens per tray during harvest

Sample	Weight (g)
T1	05.98 ^{b}
T2	**13.13** ^{a}
T3	07.64 ^{bc}
T4	08.41 ^{b}
T5	04.13 ^{c}

3.2.2 Height

The harvested microgreens were measured from the base, just above the grow medium, to the tips of the shoots. A total of 25 samples were selected randomly to measure their height. These samples were placed on a perforated high-precision scale, and the readings were recorded and tabulated in Table 4. The sample with the maximum mean height was identified as T2, which had a mean height of 5.42 cm. In contrast, the samples T1, T3, and T5 had the shortest heights, and the differences among these three samples were not statistically significant.

Table 2 - Physical testing results

Samples	GSM (g)	Strength (MPa)	Thickness (mm)	Stiffness (cm)	Sinking (s)	Wickin g(cm)
T1- Tissue paper (Control)	1.523	70	5.12	2.4	**6***	**5.98***
T2- Needle-punched Typha fiber mats	3.290	181	5.85	6.1	195	3.03
T3 - Aloe vera-treated needle-punched Typha mat	3.457	234	5.26	6.4	181	3.16
T4 - NPK-treated needle-punched Typha mat	3.681	219	5.59	6.2	175	3.23
T5 - Commercial coir mat	**8.552***	**329***	**7.73***	**8.5***	265	2.10

Table 4 - Height of the mustard microgreens during harvest

Sample	Height (cm)
T1	3.67[c]
T2	**5.42[a]**
T3	4.22[c]
T4	4.77[b]
T5	4.10[c]

3.3 Sensory Evaluation

The sensory evaluation of five microgreen samples showed consistently high acceptability across all evaluated attributes, with mean hedonic scale scores ranging from 7.2 to 8.0 and median values consistently at 8. The Shapiro–Wilk test indicated a non-normal distribution for most parameters; therefore, the Friedman test was applied. The Friedman analysis showed no statistically significant differences among the samples regarding appearance ($p = 0.067$), color ($p = 0.148$), flavor ($p = 0.534$), taste ($p = 0.131$), texture ($p = 0.598$), and overall acceptability ($p = 0.490$). Fig. 2 clearly shows that for most parameters, T2 demonstrated slightly higher values. These findings are indicated in Fig 2 and it shows that the sensory panel perceived all five microgreen samples similarly, with none demonstrating superior or inferior sensory qualities.



Figure 2 - Sensory evaluation of mustard microgreens grown on different growing media

3.4 Determination of Total Phenolic Compounds

The total phenolic compounds of all five microgreen variations are presented in Table 5. Among these samples, T4 exhibited the highest total phenolic content. This is likely due to the optimal growth conditions provided by its substrate, which ensured nutrient availability, adequate water retention, and favourable root-zone aeration. These substrate characteristics are known to enhance the biosynthesis of phenolic compounds, as they are produced in response to both nutrient supply and mild physiological stress. The increased total phenolic content of 1.34 mg/g observed in T2 suggests that its substrate created an environment conducive to the accumulation of bioactive secondary metabolites, thereby improving the overall nutraceutical quality of the microgreens.

Table 5 - Total Phenolic Compounds of mustard microgreens grown on different growing media

Samples	Total phenolic compounds (mg/g)
T1	1.28[a]
T2	1.08[b]
T3	1.05[b]
T4	**1.35[a]**
T5	1.34[a]

3.5 Determination of Chlorophylls

The values of the pigment molecules chlorophyll a, chlorophyll b, and the total chlorophyll are represented in Table 6. In microgreens, chlorophyll measurement acts as a primary indicator of the bioactive density and photosynthetic efficiency. The values of the chlorophyll content vary depending on the medium and the environment in which the microgreens are cultivated. The results from the experiment depict that the chlorophyll values of mustard microgreens grown in T1, T4, and T5 are statistically significant from the chlorophyll values of the microgreens grown in T2 and T3.

Table 6 - Chlorophyll values of mustard microgreens grown on different growing media

Samples	Chlorophyll a (mg/g)	Chlorophyll b (mg/g)	Total Chlorophyll (mg/g)
T1	0.22[a]	0.13[a]	0.34[a]
T2	0.17[b]	0.08[b]	0.25[b]
T3	0.18[b]	0.09[b]	0.27[b]
T4	**0.23[a]**	0.12[a]	**0.35[a]**
T5	0.21[ab]	**0.14[a]**	**0.35[a]**

3.6 Determination of Beta Carotins

β-carotene is an organic compound that plays an important role in neutralizing free radicals, promoting apoptosis in cancer cells, and increasing the production of natural killer cells, which in turn strengthens the immune system[22]. The beta carotene values per 100g of mustard microgreens are presented in Table 7. The T4 sample has the maximum beta carotene value of 134.20, while the minimum was noted for the T1 sample. From the values, it is clear that the addition of an NPK solution has a positive impact on the beta-carotene value of the mustard microgreen.

Table 7 - Beta carotene values of mustard microgreens grown on different growing media

Samples	Beta-carotene (mg/g)
T1	90.69[c]
T2	47.34[d]
T3	107.13[b]
T4	**134.20[a]**
T5	110.12[b]

4. Conclusion

This research highlights the promise of using invasive Typha domingensis Pers. biomass as a sustainable substrate for growing microgreens. The study explored needle-punched

nonwoven mats, both untreated and treated with aloe vera and NPK nutrients, and found that the untreated mats yielded the best results. Interestingly, the NPK-treated mats boosted the levels of beneficial compounds. Sensory evaluations showed no significant differences in taste or acceptability among the various substrates. This innovative method not only offers an eco-friendly alternative to traditional growing media but also tackles urban food sustainability and land scarcity. By transforming invasive species into biodegradable grow mats, this study supports circular bio-economy strategies and encourages sustainable farming practices in urban areas. The study had limitations, as it was conducted under controlled conditions and did not assess long-term performance, durability, or economic feasibility of the developed mats, highlighting the need for further research in diverse cultivation environments for large-scale agriculture.

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