# Design and characterisation of silica-reinforced nonwoven agricultural fabrics for plant protection and agricultural production

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**ABSTRACT – REZUMAT**

**Design and characterisation of silica-reinforced nonwoven agricultural fabrics for plant protection and agricultural production**

*Agricultural textiles protect crops from detrimental weather and pests while promoting sustainable agriculture. This research introduces an innovative nonwoven polypropylene (PP) fabric directly incorporated with silicon dioxide (silica) to diminish pesticide application. Silica acts as a physical insecticide by disrupting pests' protective wax coatings, offering an alternative to chemical pesticides that harm the environment and human health. UV-stabilized and non-stabilised polypropylene textiles were treated with silica at concentrations of 2%, 3%, and 5%. Essential qualities were evaluated, encompassing air permeability, tensile and tear strength, ageing resistance, and thermal stability (FTIR, DSC, TGA). SEM and EDS studies validated the presence and dispersion of silica. The findings indicated that silica diminished air permeability, thereby aiding in the retention of soil moisture and safeguarding plants. Although tensile and tear strength experienced minor reductions (up to 11% and 25%, respectively), the textiles continued to perform satisfactorily. Thermal investigations revealed slight alterations in decomposition temperatures. SEM–EDS showed that silica was evenly spread out but decreased a bit after ageing, suggesting that better fixing is needed for longer use. This direct incorporation of silica enhances pest control efficacy and UV resistance without dependence on chemical pesticides. The method promotes sustainable agriculture by improving crop protection and mitigating environmental hazards. Future research should concentrate on enhancing silica retention and conducting tests in actual field settings to create more robust agricultural textiles.*

***Keywords:*** *agricultural textiles, silica, non-woven, fabric, UV ageing*

**Proiectarea și caracterizarea materialelor nețesute armate cu silice pentru agricultură destinate protecției plantelor și producției agricole**

*Agrotextilele protejează culturile de condițiile meteorologice nefavorabile și de dăunători, contribuind în același timp la promovarea agriculturii durabile. Acest studiu prezintă un material nețesut inovator din polipropilenă (PP), în care este încorporată silicea, cu scopul de a reduce necesitatea utilizării pesticidelor. Silicea acționează ca un insecticid fizic prin compromiterea straturilor protectoare de ceară ale dăunătorilor, oferind o alternativă la pesticidele chimice care sunt dăunătoare pentru mediu și sănătatea umană. Materialele textile din polipropilenă, atât cele stabilizate, cât și cele nestabilizate la radiații UV, au fost supuse unor tratamente cu concentrații de silice de 2%, 3% și 5%. Au fost evaluate proprietățile esențiale, printre care permeabilitatea la aer, rezistența la tracțiune și la rupere, rezistența la îmbătrânire și stabilitatea termică (FTIR, DSC, TGA). Analizele SEM și EDS au confirmat prezența și modul de dispersie a silicei. Rezultatele au indicat că silicea a redus permeabilitatea la aer, contribuind astfel la menținerea umidității solului și la protejarea plantelor. Deși rezistența la tracțiune și la rupere a înregistrat reduceri minore (de până la 11%, respectiv 25%), materialele textile și-au păstrat performanțele la un nivel satisfăcător. Analizele termice au relevat ușoare modificări ale temperaturilor de descompunere. Analiza SEM–EDS a arătat că silicea era distribuită uniform, dar a scăzut ușor după procesul de îmbătrânire, sugerând că este necesară o fixare mai bună pentru o utilizare pe termen lung. Această încorporare directă a silicei îmbunătățește eficacitatea combaterii dăunătorilor și rezistența la radiațiile UV fără a depinde de pesticide chimice. Această metodă promovează agricultura durabilă prin îmbunătățirea protecției culturilor și atenuarea riscurilor de mediu. Studiile viitoare ar trebui să se concentreze pe îmbunătățirea retenției de silice și pe efectuarea de teste în condiții reale de teren, pentru a crea agrotextile mai rezistente.*

***Cuvinte-cheie****: agrotextile, silice, materiale nețesute, țesătură, îmbătrânire sub acțiunea razelor UV*

## INTRODUCTION

Agricultural textiles, classified as technical textiles, possess the capability to safeguard plants and products from external influences, including adverse weather, harmful insects, and various environmental factors. In 1948, the United States pioneered the use of agricultural textiles by enveloping small greenhouses with a transparent, thin paper known as cellophane. Since 1948, agricultural textiles have established a market presence, utilising various materials such as polypropylene, nylon, polyester, polyethylene, jute, and wool [1]. The agricultural textiles market is expanding and evolving daily in conjunction with population growth. In 2010, the agricultural textiles sector repre-

sented 6.4% of the technical textiles market, with sales estimated at 8.1 billion USD. This figure attained 10 billion USD in sales in 2014 and 14 billion USD in sales in 2022 [2, 3].

Contemporary agricultural textiles provide a straightforward yet efficient capacity for safeguarding against detrimental climatic factors, including hail, precipitation, wind, elevated temperatures, and ultraviolet radiation. These fabrics, because of their minute holes, establish optimal climatic conditions for plants while ensuring enough air permeability. These cloth constructions obstruct intense sunlight and, due to their capacity to reflect, absorb, and diffuse solar wavelengths, offer straightforward and efficient protection against detrimental ultraviolet (UV) radiation. In a world facing global warming, it is a fact that shade diminishes water requirements and reduces irrigation expenses [2, 4, 5].

The agricultural industry, of growing significance, employs numerous strategies to enhance product yield and diversity. The studies undertaken in the field of agricultural textiles are acquiring significant importance. Alongside technological advancements, the discovery of novel fibre materials has enhanced the diversity of fibres and the range of structures that may be constructed with these fibres. Consequently, advancements in agricultural textiles have proliferated, and these novel goods have begun to establish their presence in the market [6]. Agricultural textiles possess diverse and significant applications across the entire process, from pre-harvest to post-harvest, and continuing until the food reaches the end customer. Applications of agricultural textiles encompass moisture retention in soil, temperature regulation, nutrient loss reduction, surface greening, weed growth prevention, air permeability, germination facilitation, and the packing, shipping, and storage of agricultural products. The agricultural textiles used in these applications are expected to have key features, such as blocking sunlight and UV rays, holding water, reducing evaporation, protecting against outside conditions, being easy to transport, being affordable, and being good for the environment [7].

In recent years, there have been many new technologies in agricultural textiles, such as UV protective covers, antibacterial fabrics, pest-repellent materials with added scents or particles, and devices that generate electricity from movement.

Agricultural textiles can efficiently safeguard plants from crop pests. Their function as physical barriers renders the plants and crops they safeguard less vulnerable to assaults from birds, insects, parasites, and aphids. Pesticide spraying is presently the most recognised and often used technique for pest management in agriculture globally. Unfortunately, people still view pesticides as the traditional method of crop protection. Pesticides are chemical agents that are detrimental to undesirable organisms; they function by inhibiting the proliferation of dangerous species, repelling them, or exterminating them. In Germany, the yearly use of pesticides is estimated to be around nine kilograms per hectare [8]. Besides the detrimental impacts of pesticide application on water, soil, and beneficial organisms in agricultural regions, there are also harmful consequences on human health resulting from uncontrolled dosages and applications. Numerous studies have explored the correlation between pesticides and cancer in this domain [9, 10]. Globally, there remains a necessity for techniques that minimise pesticide usage while being environmentally sustainable and safeguarding human and animal health. Silica is also one of the primary materials used in this context. Research with silica-treated fibres is prevalent in this domain [11, 12, 13].

Research with silica seeks to offer an alternative to pesticides and diminish their application in agriculture. The term “silicate” in chemical literature denotes compounds composed of silicon and oxygen that include hydroxide ions and one or more metals, as well as silicon and silicate salts [14]. The insecticidal efficacy of silica powder relies on the absorptive dust mechanism [15]. This method suggests that the waxy layer on the outside of the insect interacts with silica dust, causing this layer to break down and be destroyed. Destruction of the protective layer that prevents desiccation in the insect leads to water loss by evaporation, ultimately resulting in the insect’s death from dehydration [14, 15, 16]. Silica powders cannot be directly applied to extensive regions due to their susceptibility to being displaced by meteorological phenomena such as wind and rain. As a result, researchers have developed diverse methodologies to integrate silica particles into textile materials [11, 17]. Unfortunately, these studies have only looked at adding silica to filament yarns, and it has been noted that using silica in these cases was also limited. Consequently, our study developed an agricultural textile by eliminating this constraint and directly integrating silica into the fabric. We assessed the benefits of the new material compared to existing materials using ageing, FTIR, TGA, SEM, and further tests. The innovative development of silica-integrated agricultural textiles represents a major milestone in the field of sustainable farming materials. By directly incorporating silica into the textile, this study overcomes the limitations associated with traditional methods of adding silica to filament yarns, paving the way for enhanced performance and durability. This approach not only enhances the functional properties of agricultural textiles but also contributes to more efficient resource use in agriculture, ultimately supporting the industry’s quest for sustainability and resilience in a changing climate.

## MATERIALS AND METHODS

### Materials

The study utilised non-woven polypropylene textiles with a basic weight of 32 g/m$^2$, including both UV-enhanced and UV-free variants. Silica, or Silicon dioxide, with the chemical formula $SiO_2$, a particle size of 100 microns, and the IUPAC designation “silicon dioxide”, was employed to deter agricultural

pests. The molar mass of silicon dioxide is 60.08 g/mol, the melting point is 1,710°C, the boiling point is 2,230°C, and the density is 2.65 g/cm³.

The printing paste was prepared using Tubivis VP 681 (ammonium salt of anionic carboxylic acid polymers, CHT, Turkey) as a synthetic thickener and Tubifast (CHT, Türkiye) as a fixative, together with a silicon dioxide additive. Table 1 below presents the abbreviations and their corresponding expansions for the samples utilised in the investigation.

Table 1

CODES AND DESCRIPTIONS FOR THE SAMPLES

| Sample code | Sample description |
|---|---|
| N1 | Silica-free and UV-added fabric |
| N2 | Silica-free and UV-free fabric |
| N1-2 | UV-added fabric with 2% silica |
| N1-3 | UV-added fabric with 3% silica |
| N1-5 | UV-added fabric with 5% silica |
| N2-2 | UV-free fabric with 2% silica |
| N2-3 | UV-free fabric with 3% silica |
| N2-5 | UV-free fabric with 5% silica |
| B-N1-5 | Pre-ageing, UV-added fabric with 5% silica |
| A-N1-5 | Post-ageing, UV-added fabric with 5% silica |
| B-N2-5 | Post-ageing, UV-free fabric with 5% silica |
| A-N2-5 | Post-ageing, UV-free fabric with 5% silica |

### Air permeability

The Textest FX 3300 Air Permeability Tester III was employed to assess the air permeability values of all fabric samples. The tests were done according to ASTM D737-04. The air permeability value is determined by the volume of air traversing a designated region of the fabric sample within a specific time interval, influenced by the airflow between the fabric surfaces. Air permeability values of the fabric samples were measured from ten distinct regions of each sample.

### Tensile strength and tear strength

The Lloyd LR5K Plus strength testing device was utilised to assess the tensile strength, percentage elongation, and tear strength of fabric samples exposed to a coating procedure based on the constant rate elongation (CRE) principle according to TS EN ISO 13934-2. Eight distinct samples were evaluated for tensile strength throughout ten repeated experiments. The specimens were fabricated to dimensions of 7×35 cm and evaluated in accordance with the specified standard, employing a pre-stress of 5.6 N and a jaw distance of 20 cm. The Elmatear Device was utilised to assess the tear strength of the fabric samples according to WSP 100.1. The testing procedure was conducted utilising the single-tear method. Eight distinct samples were evaluated for tear strength throughout ten repeated experiments. The samples were manufactured in dimensions appropriate for the B pendulum and evaluated in accordance with the specified standard. The tensile strength and tear strength tests were applied in the MD direction of nonwovens.

### Ageing

The Q-LAB QUV/spray apparatus, equipped with a Solar Eye Irradiance Control Spectrophotometer, was utilised to assess the UV transmittance values of the fabric samples. Twenty distinct samples were produced following the operational parameters of the Q-LAB brand QUV/spray utilising the Solar Eye Irradiance Control Spectrophotometer apparatus. The samples created in accordance with the device's operational specifications were dispatched to the company, and the resultant data together with the post-test samples were returned. The experimental test methodology stipulates that it will be positioned in the Q-LAB QUV/spray apparatus equipped with the Solar Eye Irradiance Control Spectrophotometer. Each 24-hour ageing cycle comprises 12 hours of ultraviolet light exposure at 50°C (0.68 W/m$^2$, utilising an UltraViolet A [UVA] 340 lamp with a spectrum closest to sunshine) followed by 12 hours of water condensation at the same temperature.

### FTIR

Fourier Transform Infrared Spectroscopy (FTIR) is an analytical technique employed to examine the chemical bonds within materials. FTIR works by measuring the spectrum created when infrared (IR) light interacts with the vibrations of the material's molecules. This spectrum serves as a distinctive fingerprint that conveys information regarding the chemical bonds of the material. Qualitative analyses of the samples were performed using a PerkinElmer Frontier FT-IR instrument within the wavelength range of 700 cm$^{-1}$ to 4000 cm$^{-1}$. The results of the fabric sample tests were documented on a computer, and the acquired data were transformed into graphs.

### DSC

Differential scanning calorimetry (DSC) is a thermal analysis method that quantifies the heat absorbed or released by a sample during heating or cooling processes. This approach involves heating the sample in comparison to a reference sample, during which the heat emitted or absorbed by the sample varies from that of the reference sample.

In DSC analysis, the sample is measured with a precision balance and subjected to heat flow as the temperature rises or falls. The sample and reference pans are fitted with heating elements and are kept at the same temperature. The thermal characteristics of the sample are depicted in the heat flow graph obtained during the temperature variation.

DSC analysis was performed in a nitrogen environment (80 ml/min) across a temperature range of 0°C to 500°C, maintaining a constant heating rate of 10°C/min with a PerkinElmer DSC 400 apparatus.

The samples were made with a mass ranging from 5 to 10 mg. The test results were documented by the computer and transformed into a graph.

### TGA

Thermogravimetric Analysis (TGA) is a thermal analysis technique that investigates the variations in the weight of a material in response to a controlled rise or decrease in temperature. A sample is typically heated at a designated, consistent temperature. The chosen temperature protocol delivers precise information regarding the sample. TGA analysis was performed to assess the thermal stability of fabric samples. The study was performed in a nitrogen environment (200 mL/min) at temperatures ranging from 30°C to 600°C, with a constant heating rate of 10°C/min. The sample's weight was calibrated to range from 5 to 10 mg. The samples for the TGA test have been adjusted to suitable dimensions and masses.

### SEM and EDS

The scanning electron microscope (SEM) is a laboratory instrument utilised for surface examination. This apparatus employs an electron beam to generate high-resolution pictures of sample surfaces. The signals produced when electrons interact with the sample provide information about the surface shape, chemical makeup, and crystal structure of the sample. Data is often gathered from a designated region of the sample surface, resulting in a two-dimensional image that illustrates spatial changes in these attributes. It was acquired with a QUANTA FEG 250 Scanning Electron Microscope (SEM). Energy Dispersive Spectroscopy (EDS) is a microanalytical method employed to identify and quantify the elements within a sample. When utilised alongside a scanning electron microscope (SEM) or a scanning transmission electron microscope (STEM), energy-dispersive spectroscopy (EDS) can provide elemental maps of samples.

## RESULTS AND DISCUSSIONS

As stated in the Materials and Methods section, the following physical properties of coated and uncoated fabrics were examined before ageing and after being kept under standard conditions.

### Air permeability

The air permeability metric is a crucial attribute in agricultural textiles. In agricultural textiles, the objective is to safeguard the plant while ensuring adequate moisture and oxygen supply. This is crucial for the plant's development.

Figure 1 displays the air permeability values of the fabrics with 2%, 3%, and 5% silica additions, alongside the unmodified reference fabrics, as determined by the air permeability equipment. The tests were performed with 10 repetitions for each sample, and the average was calculated.

The air permeability of fabrics is influenced by the fabric texture, fibre composition, yarn characteristics, ambient conditions, and the viscosity of substances applied to the fabric [18].

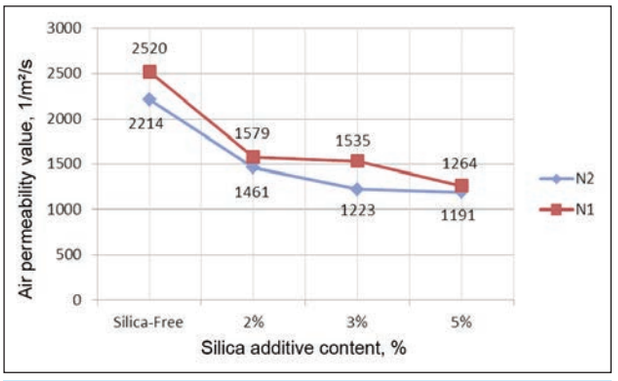



Fig. 1. Air permeability outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

The UV-free cloth (N2), exhibiting identical qualities, possesses a reduced air permeability rating. This circumstance indicates that the fibre ratio or density employed in the N2 fabric may be elevated. Post-coating, the air permeability ratings of both fabrics diminish. A 2% coating on the N1 fabric led to a 37% decrease, whereas a 34% decrease was noted on the N2 fabric. A 3% coating on the N1 cloth resulted in a 2% reduction in air permeability, but the N2 sample exhibited a 16% reduction. The N1 sample exhibited a 17% reduction with a 5% coating, but the N2 sample demonstrated a 2.6% decrease. Once the coating surpassed 5%, no additional decrease in air permeability values was noted; hence, the coating rate was not augmented further. A reduction of roughly 50% in air permeability values was recorded in the N1 fabric, and a decrease of 46% in the N2 fabric, between the uncoated and 5% coated fabrics. This also demonstrates that the coating and the results are congruent.

The average air permeability values for samples N1 and N2 are presented in figure 1. Upon examining figure 1, it is evident that an increase in silica content in both sample types correlates with a decrease in air permeability. This issue, significant for agricultural textiles, aligns with the literature when compared to prior investigations.

Now, let's support these results with correlation and regression analyses. When we examine the data in the table and graph, the basis of our analyses is the Silica Ratio (Independent Variable – *X*) and the Average Air Permeability Value (Dependent Variable – *Y*).

### N1 sample analyses

Correlation Analyses (Pearson r): The correlation coefficient (*r*) indicates the direction and strength of the relationship between two variables. The correlation coefficient (*r*) = –0.921. That value means there is a very strong and negative relationship. As the silica ratio increases, N1 values decrease significantly.

Regression Analysis: We use the equation $y = mx + c$ to model the linear relationship between the data. Slope (*m*) = –243.2, Intercept (*c*) = 2332.6, Regression

Equation: $y = -243.2x + 2332.6$, Coefficient of Determination ($R^2$) = 0.848.
The change in the silica ratio explains 84.8% of the change in N1 values. The model is reliable, but the sudden drop in the graph from 0 to 2 suggests that the relationship may not be fully linear (perhaps exponential).

### N2 sample analyses

Correlation Analyses (Pearson r): The correlation coefficient ($r$) = –0.927. Similar to N1, that value indicates there is a very strong and negative correlation in the N2 sample.
Regression Analyses: Slope ($m$) = –205.9, Intercept ($c$) = 2036.9, Regression Equation: $y = -205.9x + 2036.9$, Coefficient of Determination ($R^2$) = 0.859.
The change in silica content explains 85.9% of the change in N2 values. Sample N2 fit the linear model slightly better than sample N1.
Table 2 summarises the statistical comparison between the two samples.
For both sample groups, increasing the silica content significantly reduces the test results (measured based on the number of replicates). The decrease is particularly sharp between 0% (Silica-Free) and 2%. After this point (2%, 3%, 5%), the decrease continues, but its momentum slows.
$R^2$ values above 0.80 indicate that the negative effect of the additive content on these values is statistically significant.

### Tensile and tear strength

The tensile strength measurements of the fabric samples were performed using the Lloyd LR5K Plus strength tester, employing the constant rate elongation (CRE) method. A minimum of 10 tests were performed on each fabric sample, and the average of the findings was calculated.
The average tensile strength values for the N1 and N2 samples are presented in figure 2. Upon examination of figure 2, it is seen that the strength values

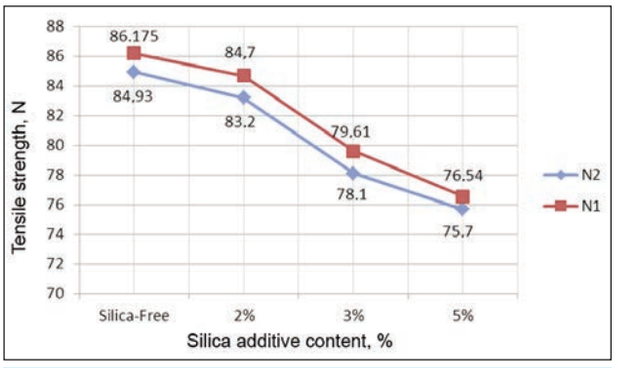



Fig. 2. Tensile strength outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

of both fabric types exhibit a slight, if not significant, decline with increasing silica content.
In the N1 fabric, the overall strength reduction decreased by 11% compared to the initial value, while in the N2 sample, it also decreased by 11%. In the N1 sample, a 2% coating results in a strength reduction of 1.7%, but in the N2 sample, the loss is 2%. As the coating quantity increases, the data exhibit a slight decline; nonetheless, the overall percentage remains at 11% for both fabrics. This condition suggests that the coating process does not substantially diminish the strength values. This is an exceptionally advantageous circumstance.
The graph shows the distribution analyses of the tensile strength of the N1 and N2 samples based on the tensile strength (tensile strength) by changing the silica additives (0%, 2%, 3%, 5%) in line with the obtained data.
Table 3 below summarises the Pearson Correlation Coefficient ($r$), the Coefficient of Determination ($R^2$), and the Linear Regression Equation for both samples.
The correlation coefficient ($r$) for both samples is very close to –1 (–0.96 and –0.97). These data show that the tensile strength of the material decreases sharply and consistently as the silica addition ratio increases.
The $R^2$ values above 0.90 (93.5% for N1, 94.1% for N2) demonstrate that the resulting linear equations

Table 2

| CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND AIR PERMEABILITY | | | |
|---|---|---|---|
| **Parameter** | **Sample N1** | **Sample N2** | **Comment** |
| Correlation ($r$) | –0.921 | –0.927 | Both have a strong negative relationship. |
| Regression equation | $y = -243.2x + 2332.6$ | $y = -205.9x + 2036.9$ | The slope for N1 is steeper, meaning that the increase in silica affects N1 more severely. |
| $R^2$ Value | 0.848 | 0.859 | The data fit the model well. |

Table 3

| CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND TENSILE STRENGTH | | | |
|---|---|---|---|
| **Sample** | **Correlation ($r$)** | **($R^2$) Value** | **Regression equation ($y = mx + c$)** |
| N1 | –0.967 | 0.935 | $y = -2.05x + 86.88$ |
| N2 | –0.970 | 0.941 | $y = -1.97x + 85.41$ |

are quite successful in explaining this data set. In other words, the decrease in tensile strength follows a largely linear trend. The coefficient of $x$ (slope) in the regression equations shows how much strength is lost with each 1% silica increase. The N1 sample loses approximately 2.05 N strength with each 1% silica increase. The N2 sample loses approximately 1.97 N strength with each 1% silica increase. According to the graph and analyses, the silica additive in this composite structure negatively affects the tensile strength.

The tear strengths of both unprocessed and processed fabric samples were measured using the Elmendorf equipment from the James H. Heal brand. Figure 3 presents the average tear strength values for samples N1 and N2. Upon examining figure 3, it is evident that an increase in silica content in both fabric types correlates with a decrease in strength values. The initial and end tear strength values for the N1 and N2 samples are similar, with a total strength loss of 25% for both N1 and N2 textiles. In the 2% coating, the loss for the N1 sample is 11%, whereas for the N2 sample, it is 15%.

Analysis of the tensile and tear strength graphs reveals that, in both sample categories, strength values diminish with an increase in silica concentration. The reduction in strength values corresponding to the rise in silica content suggests that silica contributes to a deterioration of strength in the fibre structure. This scenario indicates that the infiltration of silica between the fibres may have diminished friction and created slight alterations in the chemical structure of the fibres. The deterioration of strength in the fibre structure has directly impacted the fabric's strength. The result obtained aligns with the literature [19, 20]. Table 4 below provides a statistical summary of the relationship between the tear strength of the samples and the silica additive ratio.

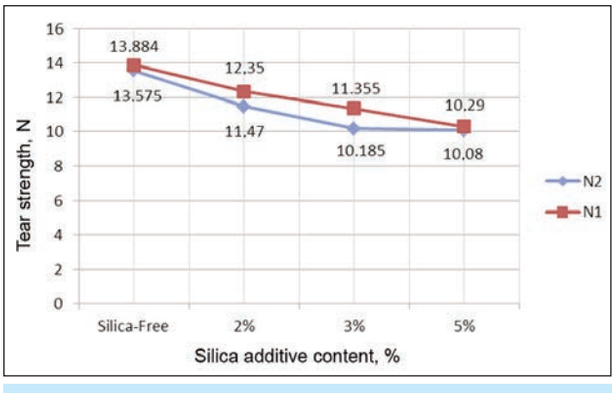



Fig. 3. Tear strength outcomes of untreated, 2%, 3%, and 5% silica-modified polypropylene fabrics

The calculated $R^2$ value for sample N1 is 0.995. This indicates that the data fit the generated regression line almost perfectly. Tear strength decreases very smoothly and linearly as the silica content increases. Each 1% addition decreases strength by approximately 0.73 N. Although the N2 sample also exhibits a generally negative trend ($r$ = –0.909), the change between 3% and 5% is minimal (from 10.185 to 10.08). This indicates a "break" or "saturation" point in the graph. While linear regression for N2 shows a general decrease, the dataset is actually more prone to a curvilinear (polynomial) behaviour. After the 3% additive rate, the strength decrease almost ceased. In both samples, silica addition reduces tear strength. Sample N1 exhibited higher strength values than N2 at all concentration levels.

## Ageing

The ageing processes of the fabric samples were conducted using the Q-LAB brand "QUV/spray with Solar Eye Irradiance Control Spectrophotometer Device". The procedure was conducted in the Paint and Colour Laboratories of MMK Metalürji San. Tic. ve Liman İşletmeciliği A.Ş. in Dörtyol, Hatay, adhering to TS EN ISO/IEC 17025 standards. The samples were created with dimensions of 7.5×15 cm, and the tests were executed. Subsequent to the testing, the sample specimens were collected for post-ageing analysis. Figure 4 presents comparative photos of the post-ageing N1-5 sample.

A pilot study using a 500-hour ageing cycle was conducted; however, upon completion, both sample types were entirely disintegrated. Consequently, it was determined to utilise 200- and 300-hour cycles



Fig. 4. Post-ageing images of non-woven fabric samples N1-5-4 (200 hours), N1-5-5 (300 hours), and N1-5-1 (500 hours)

Table 4

CORRELATION AND REGRESSION ANALYSES ABSTRACT BETWEEN SILICA CONTENT AND TEAR STRENGTH

| Sample | Correlation ($r$) | ($R^2$) Value | Regression equation ($y = mx + c$) |
|---|---|---|---|
| N1 | –0.997 | 0.995 | $y = -0.729x + 13.793$ |
| N2 | –0.909 | 0.826 | $y = -0.722x + 13.131$ |

for these samples. The samples could not undergo strength testing due to their disintegration following the ageing process (figure 4). The samples underwent FTIR, DSC, TGA, and EDS analyses, and SEM pictures were acquired both before and after the ageing procedure. Table 5 presents the sample codes and ageing durations for the samples evaluated before and after ageing.

In the analysis of the test results, the sample codes in the graphs are prefixed with the letters B or A. The symbol 'B' signifies the term 'before,' denoting the test outcome of the sample before ageing. The letter 'A' represents the coded term 'after,' denoting the test outcome of the sample post-ageing.

Table 5

FABRIC SAMPLE CODES EXPOSED TO AGEING PROCESSES AND DURATIONS

| Sample codes | Duration of exposure to ageing |
|---|---|
| N1-1 | 500 hours |
| N2-3 | 500 hours |
| N2-2 | 300 hours |
| N1-3-1 | 500 hours |
| N1-5-1 | 500 hours |
| N1-5-4 | 200 hours |
| N1-5-5 | 300 hours |
| N2-1 | 200 hours |
| N2-5-1 | 500 hours |

### FTIR test outcomes preceding and following ageing

The samples in this study were analysed using a PerkinElmer Frontier FT-IR instrument, which works with wavelengths from 700 $cm^{-1}$ to 4000 $cm^{-1}$. The FT-IR technique was utilised on the fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, and A-N2-5-1. The collected data were individually documented on the computer and transformed into graphs. Figure 5 shows the results of the FTIR tests for the nonwoven fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, and A-N2-5-1. Upon examination of figure 5, it is noted that the broad band between the wavelengths of 3200 $cm^{-1}$ and 3800 $cm^{-1}$ corresponds to the OH functional groups.

The distinctive peaks of pure polypropylene are as follows: 2949.81 $cm^{-1}$ and 2917.46 $cm^{-1}$ for C-H stretching vibrations, 1455.73 $cm^{-1}$ for $–CH_2$ bending vibrations, 1375.60 $cm^{-1}$ for $–CH_3$ bending vibrations, and 1067.22 $cm^{-1}$ for C-C stretching vibrations. The distinctive peaks of silica include 1061.94 $cm^{-1}$ for Si-O-Si stretching vibrations, 971.02 $cm^{-1}$ for Si-OH stretching vibrations, and 798.36 $cm^{-1}$ for Si-O bending vibrations [12, 20].

Upon analysis of the peaks in the FTIR spectrum, the peak at 2914.44 $cm^{-1}$ is attributed to C-H stretching vibrations, the peak at 1450.46 $cm^{-1}$ is associated with $–CH_2$ bending vibrations, the peak at 1375.24 $cm^{-1}$ corresponds to $–CH_3$ bending vibrations, and the peak at 974.05 $cm^{-1}$ is linked to C-C stretching vibrations.

### DSC

Subsequent to the DSC experiments, the relevant results were transformed into graphs depicting the fluctuation of heat flow in relation to time or temperature. Negative or positive peaks indicate exothermic or endothermic reactions, depending on the technology used in the research measuring devices. DSC graphs exhibit varying endothermic and exothermic peaks contingent upon the presence of silica in the fabrics and their ageing status.

The DSC test was conducted on samples A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1 to examine the impact of age on their thermal structure. Figure 6 below displays the graph pertaining to these samples.

In the DSC tests performed on the samples, a notable alteration was detected between the pre-ageing and post-ageing samples. The peak values in the curves of the pre-ageing samples range from 10 to 15 mW, whereas the peak values in the curves of the post-ageing samples range from 15 to 20 mW. This circumstance suggests that the crystallisation temperatures in the post-ageing samples have diminished as a result of the thermal treatment they experienced.

As seen in figure 6 above and table 6 below, the pre-ageing peak values for all samples decreased to lower temperatures after ageing. This may be attributed to the temperature-dependent degradation

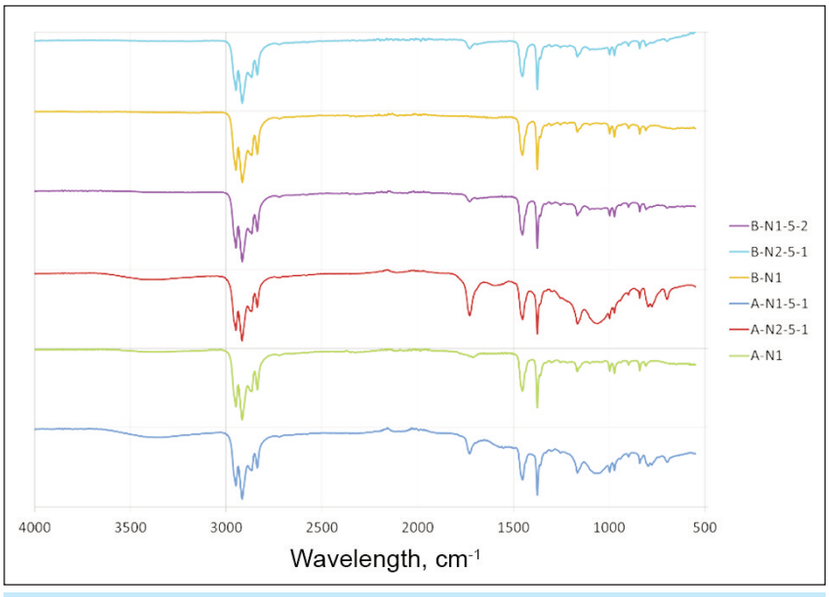



Fig. 5. FTIR test findings for non-woven fabric samples B-N1, B-N1-5-1, B-N2-5-1, A-N1, A-N1-5-1, A-N2-5-1

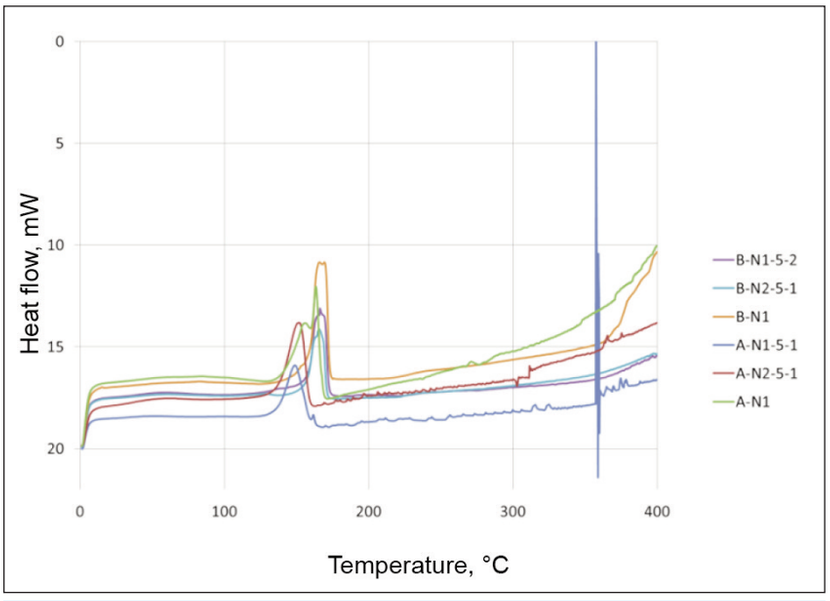



Fig. 6. Differential Scanning Calorimetry test results of fabric samples labelled A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1

Table 6

DECOMPOSITION TEMPERATURES OF SAMPLES PRE- AND POST-AGEING

| Sample codes | Temperatures (°C) |
|---|---|
| B-N1 | 168.5 |
| B-N1-5 | 166.6 |
| B-N2-5 | 166.5 |
| A-N1 | 156.6 |
| A-N2-5 | 153.0 |
| A-N2-5 | 150.0 |

of the PP constituent fabric structure during the ageing process. As seen in table 6, the degradation temperatures were higher in samples without silica additives.

## TGA

TGA analysis was performed to assess the thermal stability of fabric samples. Alternatively, it can be described as the temperature-dependent percentage mass reduction of the substance. The study was performed in a nitrogen environment (200 ml/min) at temperatures ranging from 30°C to 600°C, with a constant heating rate of 10°C/min. Sample weights were calibrated to 5–10 mg in accordance with the testing protocol.

Upon examination of figure 7, it is evident that there is no substantial difference in the early degradation temperatures of the samples. In all samples, weight loss occurs at approximately 150°C and persists until 450–500°C, except the A-N1 sample, where weight stabilises beyond this temperature range. The region between the 100% line and the 20% line represents the degradation zone of the PP polymer. The region between the 20% and 10% lines is where silica persists as a residue. This scenario aligns with the existing literature. The figure indicates that only the A-N1 sample persisted in weight loss over the 10% threshold. This circumstance suggests that the A-N1 sample included no silica as a result of the applied treatments.

The TGA data indicate that the degradation temperatures of the samples containing additional silica decreased. This scenario is inconsistent with the literature. This scenario is believed to have developed from the chemical substances employed in the printing process during the incorporation of silica [20]. The study reveals that degradation temperatures have slightly diminished with the ageing process. This condition aligns with the findings in the literature [20, 21].

## SEM – EDS Images

EDS views of the N1-5 sample's surface at 100 µm and 200 µm scales are presented in figure 8. The luminous particles in the photographs signify that the silica powder has been effectively deposited on the surface and interspersed among the fibres.

Both the pre- and post-ageing EDS pictures of the N1-5 sample, with a 20 µm pixel size, are displayed in figure 9, *a* and *b*. Analysis of figure 9 reveals that the N1-5 sample's pre-ageing silica powder content

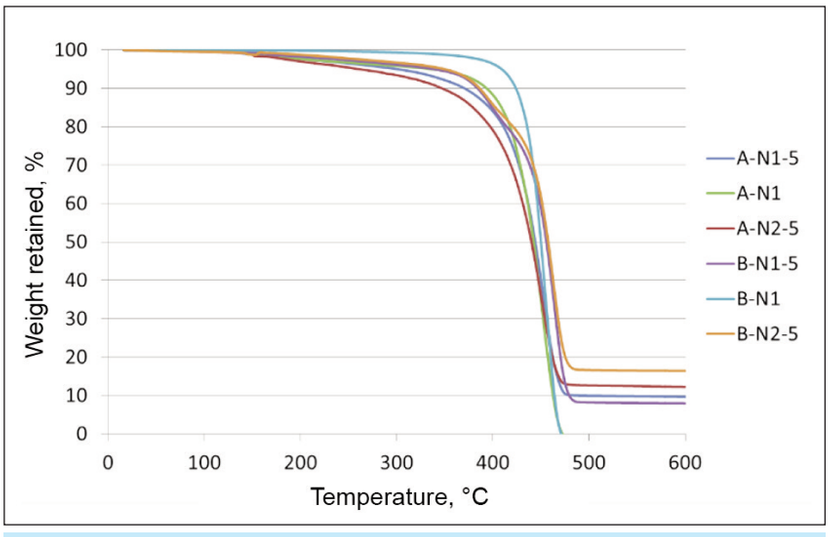
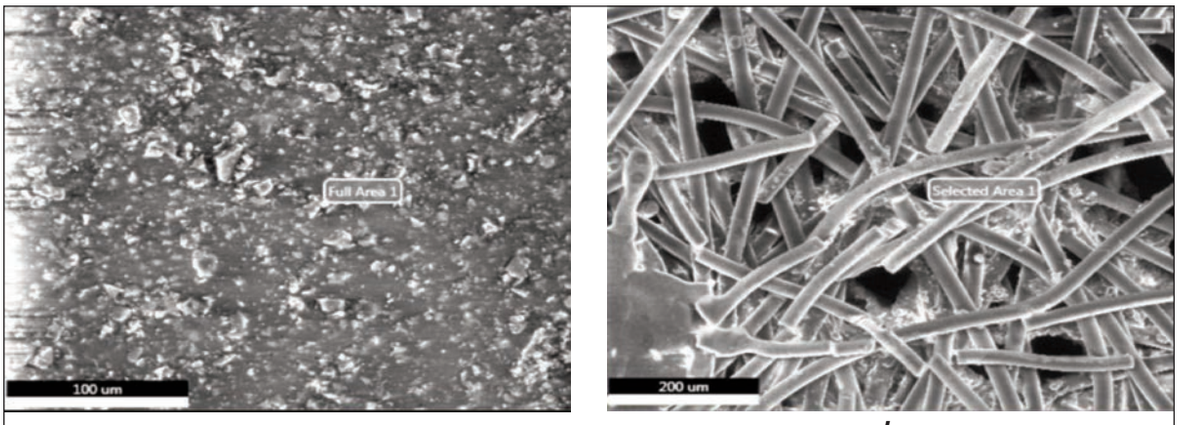
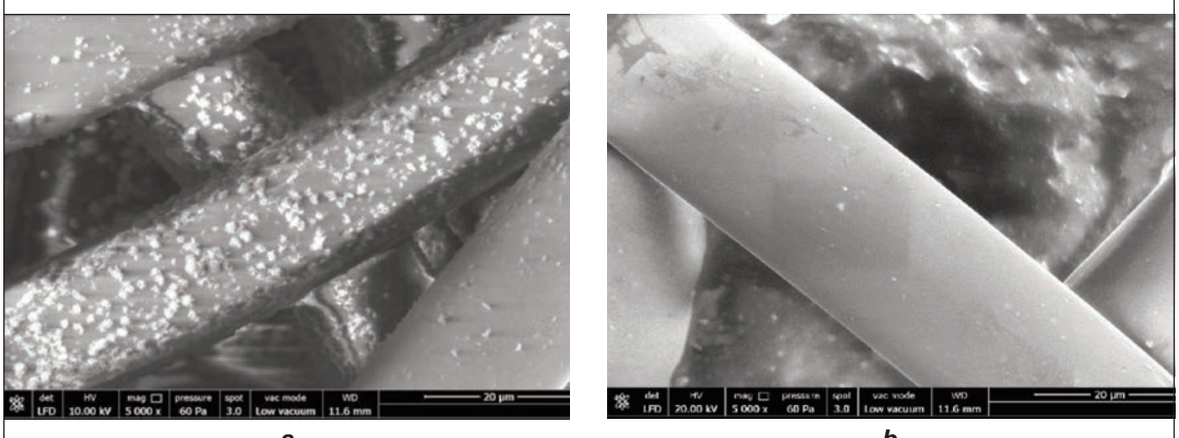



Fig. 7. The TGA test outcomes of fabric samples designated A-N1-5, A-N2-5, B-N1-5, B-N2-5, A-N1, and B-N1




*a* *b*

Fig. 8. Results of: *a* – EDS images of B-N1-5 at 100 µm; *b* – B-N1-5 at 200 µm samples



*a* *b*

Fig. 9. Results of: *a* – SEM pictures of B-N1-5 at 20 µm; *b* – A-N1-5 at 20 µm samples

has considerably dropped in comparison to its post-ageing silica powder content.

Once more, figures 10 and 11 display the N1-5 sample's EDS results both before and after ageing. The EDS point analysis of the B-N1-5 and A-N1-5 fabric samples shows the percentage of different elements found in the chemical compounds of the powders used as additives, as shown in the images from the EDS % elemental analysis results. The EDS examination revealed that the B-N1-5 and A-N1-5 samples included only carbon, oxygen, and silicon. The B-N1-5 fabric sample exhibited a carbon content of 61.04%, an oxygen content of 31.27%, and a silicon content of 7.69%. In contrast, the A-N1-5 fabric sample had a carbon content of 83.44%, an oxygen content of 14.72%, and a silicon content of 1.84%. This scenario indicates that external environmental factors, including sunlight, dew, and precipitation

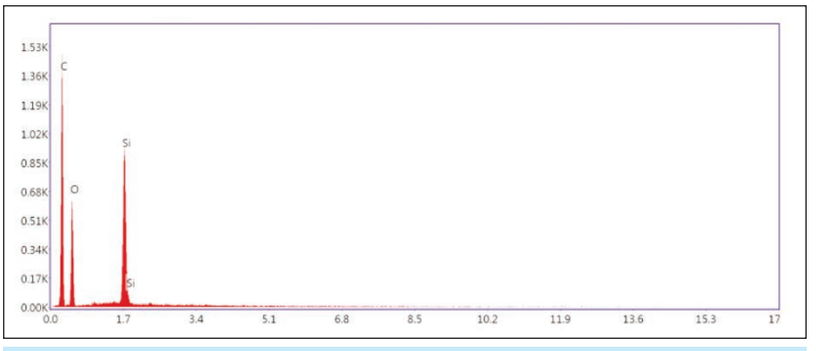



Fig. 10. EDS analysis results for sample B-N1-5

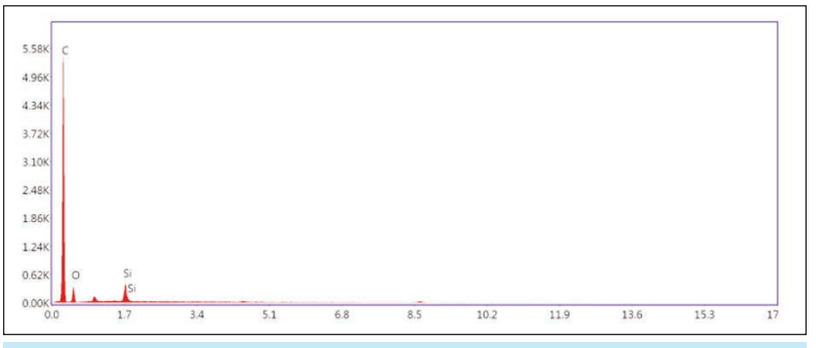



Fig. 11. EDS analysis of sample A-N1-5

during ageing, may have diminished the silica content in the fabric samples.

## CONCLUSIONS

This work produced a novel agricultural textile by incorporating silicon dioxide (silica) into both UV-stabilized and non-UV-stabilized nonwoven polypropylene (PP) textiles. The objective was to augment the protective efficacy of agricultural coverings against external elements, including adverse weather and pests, while simultaneously enhancing their resilience to ageing and durability under field circumstances.

The experimental findings indicated that the application of silica at concentrations of 2%, 3%, and 5% significantly influenced the essential physical properties of the nonwoven polypropylene textiles. Air permeability experiments indicated that a rise in silica concentration progressively diminished air permeability values. These results have also been supported by regression analyses. Silica additives have dramatically reduced the air permeability of the composite material. The greatest effect has been seen when a small amount (2%) of the additive is added, as opposed to no additive at all. Although diminished airflow may first appear disadvantageous, it can be beneficial in agricultural contexts by facilitating enhanced control of microclimatic conditions beneath the fabric, aiding in moisture retention, and safeguarding crops from pests and inclement weather. Tensile and tear strength assessments indicated that the incorporation of silica resulted in a marginal reduction in the mechanical strength of the textiles. Nevertheless, this decrease remained within permissible boundaries (about 11% in tensile strength and up to 25% in tear strength at the maximum silica concentration). Similar results have been seen in the regression analyses.

This suggests that the coating procedure did not substantially undermine the integrity of the underlying nonwoven polypropylene fabric. The findings indicate that silica particles may engage with the fibre structure by infiltrating the fibre network, potentially diminishing inter-fibre friction, which marginally influences the fabric's resistance to mechanical stress. Notwithstanding this, the textiles retained adequate strength for functional agricultural application.

The UV ageing tests validated that the silica-treated textiles demonstrated enhanced durability under accelerated weathering circumstances. While high-intensity ageing cycles of 500 hours resulted in total disintegration, modified 200- and 300-hour testing offered realistic insights into the fabrics' performance under standard UV exposure. The FTIR study verified that the chemical structure of the polypropylene matrix mostly remained unaltered, exhibiting unambiguous indications of silica integration prior to ageing and evidence of deterioration or silica loss subsequent to ageing.

Thermal investigations (DSC and TGA) indicated that the incorporation of silica and UV ageing marginally affected the thermal stability and crystallisation characteristics of the textiles. A slight decrease in thermal breakdown temperatures was noted in silica-treated samples relative to untreated samples. This phenomenon can be ascribed to the interactions between silica particles and the polypropylene matrix, along with the chemical agents employed in the fixing process. Nevertheless, thermal stability persisted within an acceptable range for standard agricultural circumstances.

SEM and EDS investigations confirmed the presence and distribution of silica particles on the fabric surfaces. Prior to ageing, the silica particles were equally distributed throughout the fibres, significantly improving the fabric's barrier function. Post-ageing SEM and EDS data revealed a significant decrease in silica concentration, presumably because of the influence of UV radiation, moisture, and various environmental variables. This discovery underscores the necessity of enhancing the fixation process to augment silica retention over prolonged use in open-field environments.

The study illustrates that the direct incorporation of silica into nonwoven agricultural textiles presents distinct advantages.

Silica functions as a physical insecticide, compromising bugs' protective barriers and diminishing reliance on toxic chemical pesticides, hence promoting environmentally sustainable pest management. The enhanced textiles retain adequate strength and permeability to shield crops from inclement weather while fostering optimal growing conditions. The improved resistance to UV degradation suggests that silica treatment can prolong the operational lifespan of crop coverings in practical environments.

In summary, the novel method of treating nonwoven polypropylene textiles with silica particles effectively tackles the dual issues of pest management and weather resistance in agricultural contexts while adhering to sustainability objectives and minimising reliance on chemical pesticides. Future research may focus on improving how silica is attached to ensure it stays longer, looking at different sizes of silica particles, and testing how well these textiles work in various weather conditions during real field trials. These enhancements would further establish silica-treated agricultural textiles as a feasible alternative for contemporary, sustainable, and resilient agriculture.

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