Science of the Total Environment 844 (2022) 157169

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility

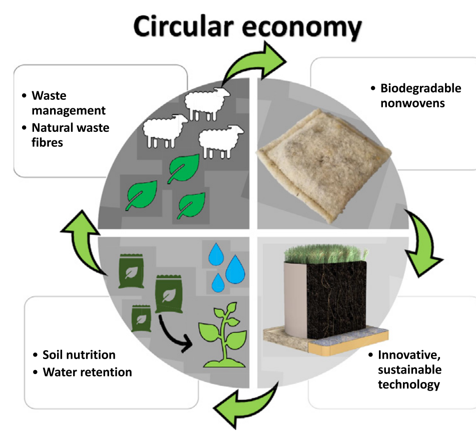
Daria Marczak [a], Krzysztof Lejcuś [a,*], Grzegorz Kulczycki [b], Jakub Misiewicz [a]

[a] Wrocław University of Environmental and Life Sciences, Institute of Environmental Engineering, Wrocław 50-363, Poland
[b] Wrocław University of Environmental and Life Sciences, Department of Plant Nutrition, Wrocław 50-363, Poland

HIGHLIGHTS

- Synthetic soil additives increase environmental pollution.
- An innovative technology to save water and support plant vegetation was demonstrated.
- The potential applications of waste fibre were analysed and proposed.
- The developed technology is in line with the circular economy.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jose Julio Ortega-Calvo

Keywords:
Circular economy
Soil nutrient
Plastic waste
Waste management
Water scarcity
Irrigation water

ABSTRACT

Human activity is accompanied by the introduction of excessive amounts of artificial materials, including geosynthetics, into the environment, causing global environmental pollution. Moreover, climate change continues to negatively affect global water resources. With the intensification of environmental problems, material reusability and water consumption limitations have been proposed. This study replaced synthetic soil additives with biodegradable materials and analysed the potential and sustainable processing of natural fibrous materials, which form problematic waste. Waste fibres are the basis of innovative soil water storage technologies in the form of biodegradable and water-absorbing geocomposites (BioWAG). We analysed the influence of BioWAGs on plant vegetation and the environment through a three-year field experiment. Furthermore, biomass increases, drought effect reductions, and biodegradation mechanisms were analysed. Natural waste fibres had a positive influence, as they released easily accessible nutrients into the soil during biodegradation. BioWAGs had a positive influence on the biometric parameters of grass, increasing biomass growth by 430 %. Our results indicated that this is an effective method of waste fibre management that offers the possibility to manufacture innovative, environmentally friendly materials in compliance with the objectives of circular economy and the expectations of users.

1. Introduction

1.1. Background

Fertile soil and water are valuable and indispensable resources that provide several ecosystem services including plant production. Soil

* Corresponding author.
E-mail address: krzysztof.lejcus@upwr.edu.pl (K. Lejcuś).

http://dx.doi.org/10.1016/j.scitotenv.2022.157169
Received 7 April 2022; Received in revised form 30 June 2022; Accepted 30 June 2022
Available online 4 July 2022

use intensification results in the excessive consumption of mineral fertilisers and water, which is currently manifested in serious environmental consequences (Hou et al., 2020; Kopittke et al., 2019). Recently, global environmental pollution, natural resource exhaustion, global warming, and soil degradation have become increasingly abundant, resulting in the deterioration of human health on an unprecedented scale (Deák et al., 2021; Faraca and Astrup, 2019; Fulton, 1999; Hanson and Weltzin, 2000; Li et al., 2022b; Sun et al., 2022; Vecchioli et al., 1990; Zhang et al., 2015). Therefore, it is crucial to identify and eliminate these undesirable phenomena while considering of sustainable development (Nghiem et al., 2021).

1.2. Soil pollution

Plastics are among the main sources of environmental pollution; however, their global demand and production continues to increase (Du et al., 2022; Singh Jadaun et al., 2022; Yang et al., 2022b). It is estimated that the production of synthetic materials contributes approximately 10 % of global petrol production, half of which serves as a raw material and half is consumed during the manufacturing process (Salvador Cesa et al., 2017). The common use of synthetic products results from their multi-functionality, ease of processing, and low prices; however, they also contribute to abundant waste production (Rochman et al., 2013; Wan et al., 2019). Only 10 % of manufactured plastics are recycled, with approximately 15 % combusted and the rest stored in landfills (Zhou et al., 2021). This way of managing plastic waste worsens the global problem of environmental pollution.

Prior research has focused on aquatic pollution and neglected soil pollution (Chaukura et al., 2021; Katare et al., 2022; Yin et al., 2021). Soils have become the dominant storage location for synthetic materials, which can negatively affect their properties. The presence of soil plastics increase evaporation and deficits of soil water content limit microbial activity and intensifies the accumulation of toxic substances that may be absorbed by plants, animals, and humans (Guo et al., 2020; Wan et al., 2019; Zang et al., 2020; Zhou et al., 2021). Geosynthetic materials are commonplace sources of soil pollution (Marczak et al., 2020b). The primary recipients of geotextiles are environmental engineering, agriculture, and horticulture, where they are used for drainage, filtration, erosion protection, separation, reinforcement, retention, and mulching (Broda, 2019; Salvador Cesa et al., 2017; Wiewel and Lamoree, 2016). These materials are manufactured from UV- and microbial-resistant synthetic fibres, allowing them to remain in the environment for years (Wiewel and Lamoree, 2016). Half of the synthetic products made are used for less than 30 d, and that period is generally limited to a single vegetation season for materials used in agriculture and environmental engineering (Hahladakis et al., 2018; Marczak et al., 2020a). Therefore, solutions that reduce the production of geotextiles from synthetic fibres are needed.

Biopolymers and fibres of plant or animal origin may prove to be the optimal solution (Marczak et al., 2020a; Santos et al., 2021). Biopolymers are becoming increasingly popular, but they are expensive and not readily available (Platnieks et al., 2021); however, commonly available natural fibres are often low-quality waste materials (Al Faruque et al., 2021; Bousshine et al., 2022; Fang et al., 2022). For example, only 45 % of the annual production of sheep wool is introduced into the market, while the rest is stored for years or kept on farms as problematic waste (Corscadden et al., 2014). Animal and plant originating resources are easily accessible nutrient sources for plants (Marczak et al., 2020b), making them an option for field applications (Marques et al., 2014).

Natural fibres work well for short-term applications, where post-degradation plant cover is sufficiently developed to survive subsequent vegetation seasons (Broda et al., 2020; Nguyen et al., 2021; Prambauer et al., 2019). Therefore, biodegradable materials are used successfully in road construction, embankment reinforcement, water reservoir banks, strengthening high-earthen walls, landfill construction, and drainage of roads and squares (Cao et al., 2020; Sarsby, 2007; Subaida et al., 2009; Venkateswarlu et al., 2018). Additionally, the use of waste resources matches the objectives of a circular economy and offers the possibility of pursuing the goals of sustainable development, which assumes reductions in the volume of generated waste, improvements in resource use efficiency, and strengthened environmental protections (Czuba et al., 2021; Das et al., 2022; Ogunmakinde et al., 2022).

1.3. Water deficit

The results of the improper use of soils are worsened by rapidly progressing water deficits and climate change (Baghbanzadeh et al., 2017). According to prognoses, the situation will deteriorate dynamically in the upcoming years, and nearly two billion people may be affected by limited access to water (Roa et al., 2021). The long-term consequences of droughts are particularly severe in countries with strong agricultural sectors that consume approximately 3/4 of their available water resources (Carrão et al., 2016; Dan et al., 2011; Jury and Vaux, 2007; McLaughlin, 1985; Meza et al., 2021; Myint et al., 2021; Steele et al., 2018). Solutions that improve water retention and limit nutrient removal are essential to achieving satisfactory yields and reducing negative environmental impacts (Anagnostopoulou et al., 2022; Jatav et al., 2021; Li et al., 2022a). Every action aimed at improving the retention of water and nutrients in soil may limit these undesirable phenomena.

1.4. Consumption of mineral fertilisers

Poor soil quality and water deficits are usually accompanied by substantial usage of mineral fertilisers (Bisht and Chauhan, 2020; Good and Beatty, 2011; Szogi et al., 2021; Usowicz and Lipiec, 2022). Soil fertilisation uses minerals and organic substances to enrich the soil with nutrients necessary for plants (Igalavithana et al., 2015; Jatav et al., 2021). Fertiliser misapplication has seen a decrease recently but persists. Incorrect fertiliser application is undesirable, economically unjustified, and has a negative impact on the environment (Kopittke et al., 2019; Li et al., 2022c). Additionally, long-term fertiliser application can lead to numerous adverse effects on soil and groundwater properties, such as soil pollution and acidification, microbial activity reduction, and water eutrophication (Coskun et al., 2017; Kayastha et al., 2022; Timonen et al., 2019; Walling and Vaneeckhaute, 2020). Nitrogen fertiliser application contributes to N_2O emissions and increases the effects of global warming (Shcherbak et al., 2014). Additionally, the awareness of farmers is increasing and they are increasingly looking for and implementing good agronomic practices. Therefore, we should strive to develop sustainable practices to increase the efficient use of nutrients by employing slow-release solutions. The popularisation of new soil additives with a sustainable composition may reduce the use of mineral fertilisers, which have dominated plant cultivation for years (An et al., 2022; Chehade and Dincer, 2021; Erisman et al., 2008).

1.5. Alternative solutions

Sustainable soil practices, such as reducing the use of mineral fertilisers, building soil fertility through the use of natural soil additives, using water resources efficiently, and properly managing waste, are designed to combat soil degradation, support formation, and soil health (Bünemann et al., 2018; Buzzard et al., 2021; Sharma et al., 2022). Scientists have been investigating new methods of improving the retention capacity and fertility of poor soils, mainly sandy soils with low organic matter content (Ding et al., 2016; Szogi et al., 2021). A popular method is using soil additives, of which compost, manure, and biochar are the most commonly used (Adediran et al., 2012; Cybulak et al., 2021; El-mrini et al., 2022; Regni et al., 2017). The most attractive soil additives that improve retention include zeolite, bentonite, superabsorbent polymers (SAP), also known as hydrogels, and the relatively new water-absorbing geocomposites (WAG) (Singh et al., 2021; Śpitalniak et al., 2021). Zeolites are synthetic aluminium silicates that consist of a system of connected chambers and channels, which gives them a high sorption capacity (Gatta and Lotti, 2019; Szerement et al., 2021). Bentonites are clayey rocks which, owing to their structure and swelling capacity, improve the retention capacity of the soil (Manjaiah et al., 2019; Mi et al., 2017). Despite their advantages, these additives do not have as high of a water retention capacity as SAP (Śpitalniak et al., 2021). SAPs are powdered or granulated polymers, a dry gram of which can absorb up to 300–400 g of water (Lejcuś et al., 2015a). The primary task of SAPs is to absorb, store, and supply water to the plant when necessary. Hydrogels also reduce the use of fertilisers, while improving soil properties (Arican et al., 2021; Lejcuś et al., 2015b; Miljković et al., 2021). The selected types of SAP are not toxic to plants or the environment, and if they are applied in actual field conditions, they are subject to gradual degradation (Oksińska et al., 2016; Xiong et al., 2018; Zhao et al., 2008). Unfortunately, the field application of superabsorbents has certain limitations. As an additive that improves the retention capacity of soil, it is mixed directly with the substrate, which significantly limits its sorption capacity (Misiewicz et al., 2019a).

WAGs are a new type of soil additive with a spatial structure that fully benefits from the sorption capacity of superabsorbent polymers and eliminates some notable limitations. This innovative technology enables efficient water retention in the soil. Later, the water is absorbed by plant roots (Bąbelewski et al., 2017; Lejcuś et al., 2015b). Depending on the application, geocomposites may have various shapes and sizes, but they are usually applied as a mat (Śpitalniak et al., 2021). The basic version of the WAG consists of a nonwoven geotextile, internal skeleton structure, and SAP. The permeable synthetic nonwoven fabric absorbs water from the environment and transports it to the interior of the WAG, where it is stored in the SAP. The skeleton structure is a synthetic spatial grid that captures the loads and creates a free space for the swelling of SAP (Lejcuś et al., 2018; Marczak et al., 2020a; Oksińska et al., 2016). This study investigated a new biodegradable version of a water-absorbing geocomposite (BioWAG). As such, the synthetic skeleton structure and textile were replaced by fully biodegradable materials of from plants and animals, so that nutrients are slowly released into the substrate, while the environment is kept in good condition. BioWAG is one of the few solutions which improves water retention and provides a source of nutrients for plants.

1.6. Significance and aim of the research

This study considered the connection between reasonable plant growth support, saving the water necessary for irrigation, a circular economy, and sustainable development goals. This research constitutes the basis for the introduction of innovative solutions related to interdisciplinary measures that limit the spread of the effects of droughts and soil pollution and prevent the generation of agricultural waste. These actions lead to the development of a new technology for the reasonable support of vegetation that considers the reuse of materials.

The major objective of this study was to determine BioWAG effectiveness under field conditions. Further, we aimed to identify the processes that accompany the biodegradation of textile materials and determine the usability of biodegradable nonwoven materials in field applications. This study exemplifies the need to adopt a rational approach to soil additives and lists the methods of sustainable management of textile waste in the environment. We also discussed general information about soil pollution from synthetic materials and mineral fertilisers and the aspects of reasonable water management. Waste textile material management deficiencies were identified, and the properties of such materials on innovative WAGs were determined. The aspects presented in this study constitute a basis for the promotion of sustainable technologies and management of environmental pollution.

This study is a response to contemporary socioenvironmental needs that addresses a gap in the literature. Most available studies on geotextiles have been conducted in laboratories or in short-term field experiments, which may not consider the long-term effects of their application in actual conditions.

2. Materials and methods

2.1. Test materials

2.1.1. Internal skeleton structure and the superabsorbent (SAP)

This research was conducted on a BioWAG consisting of nonwoven, internal skeleton structure, and SAP. The internal skeleton structure was constructed from wood to create an openwork spatial structure. BioWAG uses a co-polymer of acrylamide and potassium acrylate (Aquasorb 3005 KL; SNF Floerger; Andrézieux, France). The selected SAP was commonly used in agricultural and environmental engineering applications and is a dry granulate that takes the form of a transparent gel under the influence of water. Aquasorb is non-toxic and undergoes gradual biodegradation under the influence of selected environmental factors, such as certain bacteria that are naturally present in soil (Oksińska et al., 2016, 2019). Selected soil bacteria, such as *Enterococcus faecalis*, *Geobacillus thermoglucosidasius*, *Klebsiella pneumoniae*, *Variovorax boronicumulans*, *Kluyvera georgiana*, and *Bacillus sphaericus*, may reduce and gradually degrade the polyacrylamide concentrations (Guezennec et al., 2014; Matsuoka et al., 2002).

2.1.2. Textile

Biodegradable nonwovens were manufactured from three types of natural animal/plant fibres, that is, wool, jute, and linen (Fig. 1). The selected fibres were characterised by appropriate strength parameters, such as waste materials, environmental friendliness, and their gradual biodegradation causes the release of nutrients that are accessible to plants. The detailed strength parameters and hydraulic and chemical properties of the nonwovens were presented by Marczak et al. (2020a). The control sites are marked with the symbol K and consist of soil without soil additives.

2.1.3. Composite fabrication

For the purposes of the experiment, BioWAG prototypes were prepared in the form of spatial mats of a 0.22 m length, 0.22 m width, and 0.02 m height. The stages of prototype preparation are shown in Fig. 2.

2.2. Test area and plan of the experiment

2.2.1. Research area

This study was conducted from May 2018 to October 2020 in a test field located near the Agricultural and Hydrological Observatory Wrocław-Swojec (51°07′N, 17°10′E) of the Wroclaw University of Environmental and Life Sciences in southwestern Poland. This observatory is situated in a warm, moderate-climate zone. Detailed data on temperature and rainfall during the analysed period are presented in Fig. 3. The average monthly temperatures in 2018 ranged from 5.3 °C (November) to 21.7 °C (August). The total rainfall ranged from 11 mm (August) to 73 mm (July). In 2019, the average monthly temperature ranged from 6.9 °C (November) to 22.5 °C (June), while the total monthly rainfall ranged from 23 mm (June) to 93 mm (May). In 2020 the average monthly temperatures ranged from 5.7 °C (November) to 20.2 °C (August), and the total monthly rainfall ranged from 10 mm (April) to 192 mm (June).

2.2.2. Characteristics of the experimental sites

Before placing them in the soil, the prepared BioWAG prototypes were soaked in tap water until full SAP swelling. In the field, 0.30 m holes were prepared, and their walls were layered with a synthetic sheath (diameter of 0.20 m). This ensured that they would have the same capacity necessary for the development of the plant root system and allowed for comparison of the biometric parameters of plants. One BioWAG of the given type was placed on the bottom of the holes and then covered with a 0.15 m thick layer of fertile soil (loamy sand) (Fig. 4). The research area was covered with loamy sand, classified according to the United States Department of Agriculture (USDA) classification (Misiewicz et al., 2019b). On the surface of each site, 0.63 g of seeds of an appropriately selected mixture of grasses was sown on the surface of each site (65 %

sample **BA**- washed wool (99.4%) and artificial seams (0.6%), seamed nonwoven

sample **BB**- washed wool (100%), needle punched nonwoven

sample **BC**- washed wool (90%) and jute (10%), needle punched nonwoven

sample **BD**- washed wool (90%) and jute (10%), seamed nonwoven

sample **BE**- washed wool (50%) and linen (50%), needle punched nonwoven

Fig. 1. Nonwovens used in the field experiment.

Lolium perenne; 5 % *Poa pratensis*; 20 % *Festuca rubra*; and 5 % *Festuca ovina*, according to the manufacturer recommendations of 200 kg/ha).

2.2.3. Course of the experiment

The experiment was conducted in a field divided into three blocks of the same dimensions (1.5 × 5.5 m), with buffer zones of 1 m width. Each of the blocks referred to one vegetation season and was removed at the end of the season to collect samples for analysis. In each block, five BioWAG variants and control sites (without additives) were applied. Each variant was repeated 6 replications within a given block and 108 sites were created in three blocks. The samples were distributed in the field in uniformly placed rows, eliminating the influence of the threshold conditions. Rows containing specific BioWAG variants were randomly placed. Irrigation was conducted only during the initial phase of the experiment, that is, until grass emerged. At which point, the amount of water in the BioWAGs depended only on atmospheric conditions. Throughout the experiment, neither additional fertilisation nor spraying against insects or diseases were used, and weeds were manually removed during the vegetation period.

The development of the aboveground parts of the grass was monitored regularly for three vegetation seasons based on the visual assessment of plant conditions, increase in biomass, and the water balance of the plants. At the turn of October and November each year, another block of the experiment was removed to determine the biometric parameters of the root systems and analyse BioWAG conditions.

2.2.4. Assessment of plant material

The following elements of plant material were assessed: fresh and dry weight of the aboveground parts of grass, and the length, density, and dry weight of the root system. The aboveground parts of the plants were collected at 7–8 week intervals. The grass was cut with shears as close as possible to the ground. The area from which the grass was harvested was determined by the synthetic cover and was 0.0314 m^2. The pieces were placed in marked zip-lock bags and immediately transported to the laboratory. The dry weight of grass was determined after drying the grass in a laboratory dryer at the 70 °C until the weight was constant.

1. • Preparation of nonwovens of the dimensions 0.22x0.44 m.
2. • Folding the nonwoven in half and sewing the edges together to form a "pocket"
3. • Filling the "pocket" with wooden skeleton structure and dry SAP granulles.
4. • Closing the top edges.

Fig. 2. Preparation of BioWAG prototypes.

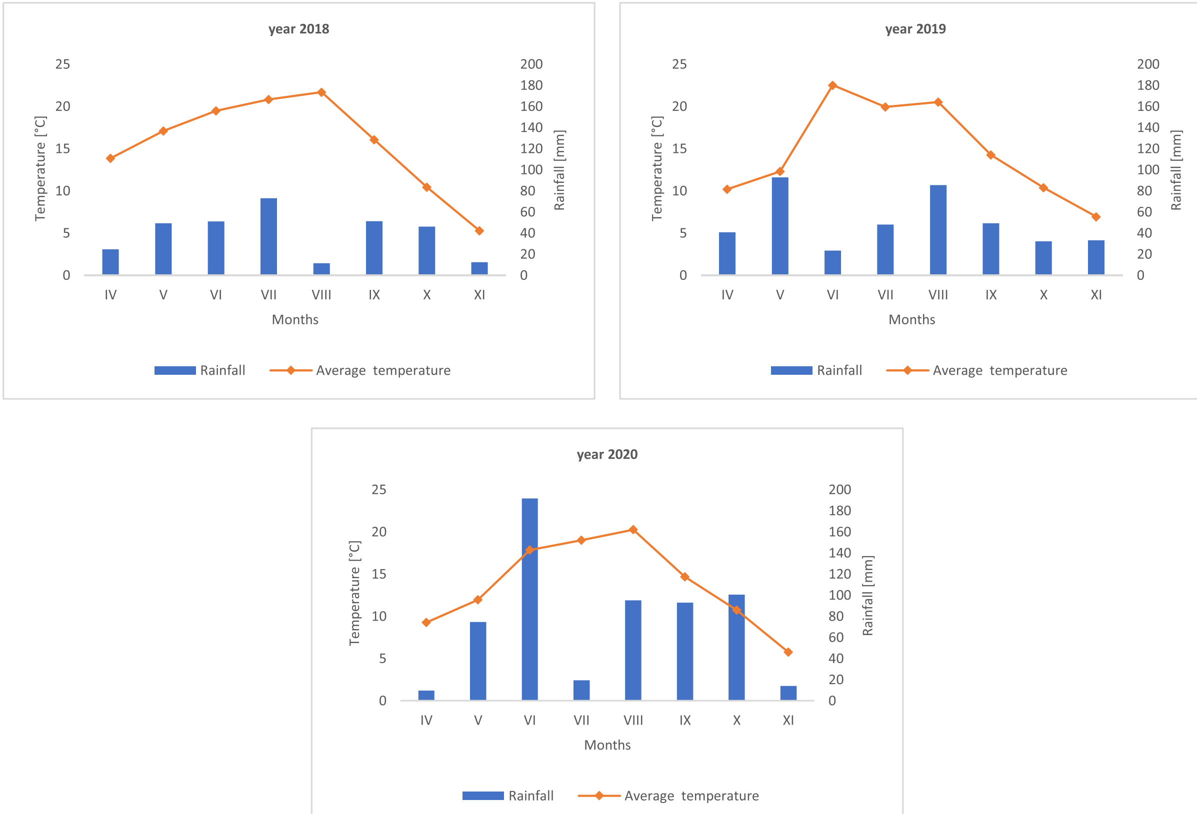


Fig. 3. Average monthly temperatures and total rainfall noted in the years 2018–2020.

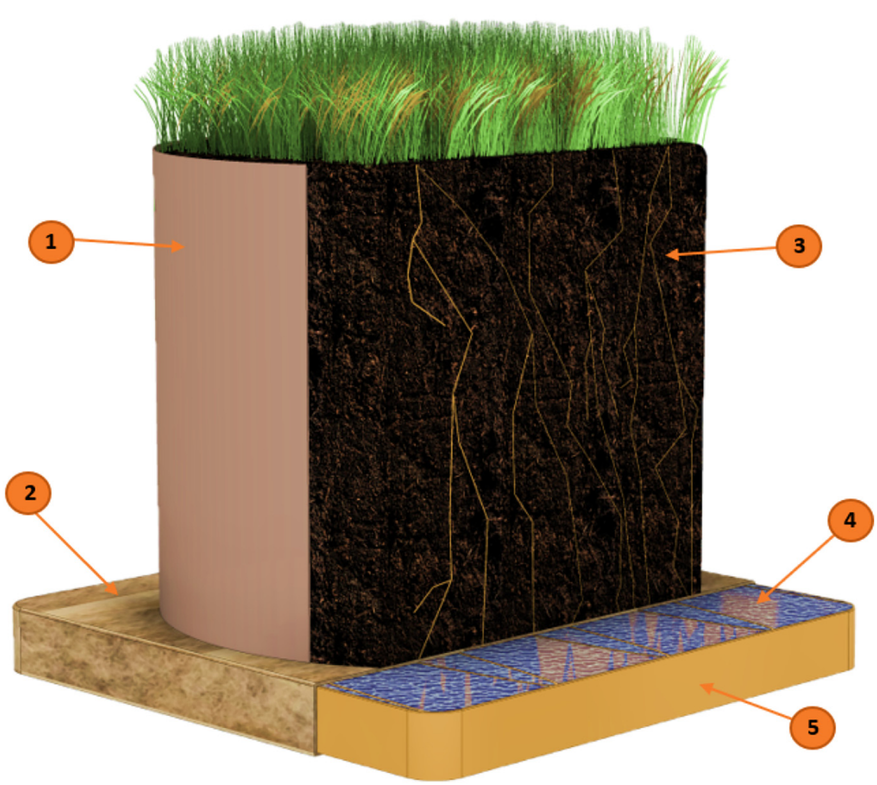


Fig. 4. Layout of the test site: 1-synthetic cover; 2-nonwoven; 3-soil; 4-superabsorbent (SAP); 5-internal structure.

2.2.5. Relative water content (RWC)

Fresh blades of grass were analysed for water content using a relative water content (RWC) indicator. Measurements were taken at 7–8 week intervals, and they were preceded by the determination of the fresh and dry weights (according to Section 2.2.4.). and turgid weight, which was obtained after the leaves remained in distilled water for 24 h and were delicately surface dried with a paper towel (Ahmad et al., 2022). RWC was calculated using the equations presented in Table 1.

2.2.6. Root system

The root systems of the plants were collected at the end of the vegetation season. To extract the root system, a hole was manually made around the synthetic cover with a spade. The root system was collected from BioWAG, which was located at the bottom of the hole. They were protected with stretch foil and transported to the laboratory. Photographic documentation was completed and BioWAG samples were collected for analysis. First, excess soil was removed from the root system, and the roots were thoroughly washed with water. The dry weights of the samples were determined after drying the root systems in a laboratory dryer at 70 °C, until the weight was constant. The length, density, and root length density of the root systems were determined based on the equations presented in Table 1.

2.2.7. Analysis of the chemical composition of plants and soil properties

Soil samples for chemical analysis were collected in the fall of 2020. After removing BioWAG and the root system, six complete soil samples were collected at a depth of 15–20 cm. Each complete sample consisted of four single samples. Control samples were collected from six randomly selected sites in the experimental field at depth of 15–20 cm. The control consisted of four samples. All the samples were transported to the laboratory in grip-sealed bags and subjected to analysis.

After preparing the soil material, the following was determined: soil pH of 1 mol/dm^3 KCl using the potentiometric method and nitrogen (N organic). The nitrogen content was determined using the Kjeldahl method (Bremner, 1960). The content of plant-available phosphorus and potassium was determined using the Egner–Riehm method and the content of soluble magnesium was determined using the Schachtschabel method. The contents of soluble micronutrients in the tested soils, such as Mn, Fe, Cu, and Zn, were determined by the Rinkis method using an AAS (Varian model SpectrAA 220FS, Varian Medical Systems, Inc., Charlottesville, VA, USA) (Kulczycki and Sacała, 2020). Baseline soil nutrient values are presented and analysed in the results. These are marked with symbol K (control).

The grain-size distribution of the soils used in this study was determined via sieving. The test was performed on 500 g of air-dried samples, which were screened through a set of six sieves with mesh sizes of 0.10, 0.25, 0.50, 1.00, 2.00, and 5.00 mm. For the leftover fraction from the sieving method, hydrometer analysis was conducted (Misiewicz et al., 2019b). Soil samples for bulk density analysis were collected with 100 cm^{-3} Kopecky metal rings once during the experimental period in 2018. The soil bulk density was determined using the bulk density test. Soil organic material (SOM) was determined as the percentage of weight loss before and after combustion at 400 °C.

In plant material collected during the research the overall level of nitrogen (N organic) was determined with the Elementar vario MACRO cube method and the overall level of S (S total) was determined with the Butters–Chenery method (Kulczycki and Sacała, 2020). To determine other elements, the plant material was dry mineralised and the ash was taken up with nitric acid and determined in solutions, using the vanadic-molybdate method to determine phosphorous and flame photometry to determine potassium.

2.2.8. Absorption capacity of the SAP

The hydrogel swelling degree was 20 °C, as determined through the tea-bag method (the average weight of the dry bag was 6.55 g), with distilled water as the liquid to be absorbed. SAP samples were collected from BioWAG from the experimental plot, with five replications for each year. SAP samples were cleaned of root system remnants and soil, and dried in a laboratory drier at 70 °C. The control samples were pure SAPs that were introduced into the environment. Then, 1 g of hydrogel was put into the bag and fully immersed in water at 20 °C. After 5, 10, 30, 60, 120, 240, and 1440 min, the wet bag with the hydrogel was removed from the water and placed on a dry cloth to drain excess water. The hydrogel was then weighed in a bag. These actions were repeated at each time interval. The sorption capacity of SAP was calculated as follows (Zhang et al., 2020):

$$AC = \frac{m_3 - m_2 - m_1}{m_1} \left[\frac{g}{g}\right]$$

where m_1 is the weight of dry SAP [g], m_2 is the weight of the bag [g], and m_3 is the weight of the bag with swollen SAP [g].

2.2.9. Statistical analyses

The results were subjected to one-way analysis of variance. Prior to performing the analysis of variance, tests for homogeneity of variance within groups were performed using Levene's test and the Shapiro–Wilk test of the correspondence of variables to the normal distribution. The relevance of the mean differences was evaluated using Tukey's post hoc test with a significance level of $p = 0.05$. The statistical program R was used for all the statistical analyses (Team, 2020).

3. Results

3.1. Assessment of plant material

BioWAGs were applied to the test field in May 2018. After several weeks, the sites were overgrown by turf. At sites where BioWAGs were applied, the turf created a dense, cohesive structure of an intensely green colour, which was particularly noticeable during the first two vegetation seasons (i.e., years 2018 and 2019) (Fig. 5).

3.1.1. Fresh and dry mass yield

During the first vegetation season, three swaths were analysed. The fresh weight of the grass was, on average, 240–430 % higher than that of the control sites. With respect to dry weight, an increase in growth by nearly 200–400 % was observed compared to the control sites. The presented results demonstrated very high efficiency of all types of BioWAGs in terms of increasing growth of the aboveground parts of the plants (Table 2). The best results were obtained on the site marked as BA, and the lowest efficiency was noted on site BE.

During the second vegetation season, three swaths were analysed. The fresh weight of the grass was, on average, 200–300 % higher than that of

Table 1
Formulas used to determine individual parameters.

Parameter	Formula	Unit	Symbols
Density	$\rho = \frac{m}{V}$	$\left[\frac{g}{m^3}\right]$	m- dry weight [g] V- site volume [m^3]
Root length density (RLD)	$\mathrm{RLD} = \frac{L_T}{V}$	$\left[\frac{m}{m^3}\right]$	L_T- total length of the root system [m] V- site volume [m^3]
Relative water content (RWC)	$RWC = \frac{FW - DW}{TW - DW} \cdot 100$	[%]	FW-fresh weight [g] DW-dry weight [g] TW-turgid weight [g]

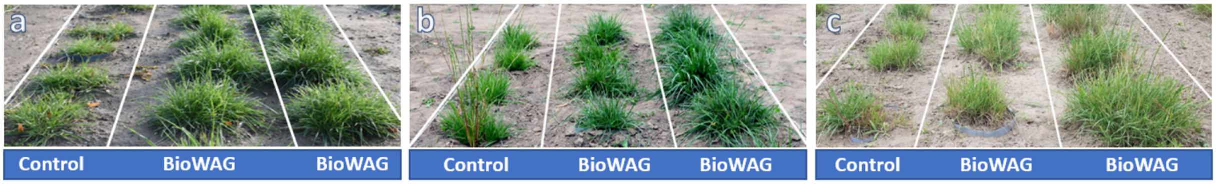


Fig. 5. Condition of the test sites in the years: a-2018, b-2019, c-2020.

Table 2
Average increase in fresh and dry mass of grass in the years 2018–2020; Values indicated by the same letter are not significantly different (a = 0.05).

Designation of the position	I year		II year		III year	
	Fresh mass [g]	Dry mass [g]	Fresh mass [g]	Dry mass [g]	Fresh mass [g]	Dry mass [g]
K	11.4 b	3.5 b	10.2 c	3.6 d	9.0 b	3.5 c
BA	60.2 a	17.7 a	39.0 a	13.6 a	13.7 a	5.0 ab
BB	54.7 a	16.5 a	38.1 a	13.2 ab	13.0 a	4.9 ab
BC	52.6 a	15.0 a	30.6 b	10.7 bc	12.5 a	4.4 b
BD	57.3 a	17.2 a	40.4 a	14.1 a	14.0 a	5.3 a
BE	38.8 a	11.2 a	31.1 b	10.6 c	12.4 a	4.5 b

the control sites. As for dry weight, an increase in growth of nearly 200–290 % was observed compared to the control sites. At this time, the highest efficiency was noted at the BD site and the lowest at the BC site; however, a very high BioWAG efficiency was noted at all sites compared with the control sites (Table 2).

During the third vegetation season, three swaths were analysed. The fresh weight of the grass was, on average, 40–55 % higher than that of the control sites. The dry weight increased by nearly 30–50 % compared to the control sites. The highest efficiency was noted at the BD site and the lowest on the BE site (Table 2).

3.2. Development of the grass root system

Analysis of the average growth of the root system during 2018–2020 demonstrated that BioWAGs were highly efficient in field applications. The addition of BioWAGs resulted in very strong root system development and improved the tillering of grass (Fig. 6).

Again, the best results were noted during the first vegetation season, when both the dry weight and density of the root system were 130–220 % higher than those of the control sites. In subsequent years, the growth in weight and density increased by 120–186 % and 73–120 % in 2019 and 2020, respectively. BioWAG application also had a positive influence on other biometric parameters of the root systems, such as RLD, length, and density. The average length and RLD index of the root system of grass were higher by 17–36 %, 24–32 %, and 24–38 % during 2018, 2019, and 2020, respectively, compared to the control sites (Table 3).

3.3. The influence of BioWAG on the relative water content (RWC) indicator

The RWC indicator reflects the relative water content in the leaves, which enables the determination of the influence of external conditions on the water stress of plants and their ability to survive under specific conditions. The presence of BioWAG increased the RWC by 18–21 % in the first vegetation season, 25–32 % in the second vegetation season, and–26–33 % in the third vegetation season (Fig. 7).

3.4. Analysis of the chemical composition of plants and soil properties

BioWAG application noticeably increased the absorption of microelements in all three vegetation seasons (Fig. 8). During the first vegetation season, nitrogen absorption was 178–513 % higher than that at the control sites. Significant differences were also noted for sulphur (absorption increased by 300–450 %), phosphorus (increase by 250–450 %), and potassium (increase of 277–508 %). This trend was also maintained during the second vegetation season, when nitrogen absorption was increased by 300–392 %, sulphur by 231–372 %, phosphorus by 229–390 %, and potassium by 216–367 % compared to the control sites. During the third vegetation season, the nitrogen absorption was increased by 47–62 %, that of S by 78–112 %, that of P by 35–76 %, and that of K by 76–120 %.

Fig. 6. Development of the root system on a control site and a site with BioWAG in the years 2018–2020.

Table 3
Average biometric parameters of the grass root systems in the years 2018–2020; Values indicated by the same letter are not significantly different (a = 0.05).

Designation of the position	Mass [g]	Length [m]	Density [g/m³]	RLD [m/m³]
I year				
K	1.92 b	0.19 c	306.00 b	30.79 c
BA	6.10 a	0.24 ab	970.81 a	38.22 ab
BB	6.04 a	0.26 a	962.05 a	41.93 a
BC	4.49 a	0.24 ab	714.44 a	37.95 ab
BD	5.05 a	0.23 b	803.34 a	36.09 b
BE	4.50 a	0.25 ab	717.09 a	39.28 ab
II year				
K	1.93 b	0.18 b	307.86 b	29.19 b
BA	5.53 a	0.24 a	880.84 a	37.95 a
BB	5.25 a	0.24 a	835.19 a	38.75 a
BC	4.30 a	0.23 a	684.71 a	36.36 a
BD	5.49 a	0.24 a	874.47 a	38.22 a
BE	4.34 a	0.22 a	691.35 a	35.03 a
III year				
K	1.63 b	0.17 b	260.08 b	27.07 b
BA	3.50 a	0.23 a	557.59 a	36.36 a
BB	3.57 a	0.23 a	568.74 a	35.83 a
BC	2.83 a	0.22 a	450.37 a	34.50 a
BD	3.63 a	0.24 a	578.29 a	37.42 a
BE	2.99 a	0.21 a	475.32 a	33.70 a

The soil in the test plot was classified as a loamy sand. The soil was characterised by a broad distribution of grain sizes, with a mean diameter of 0.49 mm. Fig. 9 shows the range of grain sizes. The basic properties of the soils used in this study are presented in Table 4.

Chemical property changes in the soil after three years are summarised in Table 5. The application of BioWAGs did not cause significant changes in the soil pH after the study period. The most significant changes in the chemical composition were noted for phosphorus, whose share after three vegetation seasons was 26–81 % higher than that in the control sites. Significant differences were also observed in the case of nitrogen content, which was 15–70 % higher at the BioWAG sites than that of the control. Additionally, the soil at sites where BioWAGs were installed was richer in magnesium, the content of which was increased by 18 %. As for phosphorus, manganese, copper, iron, and zinc, a decrease in their contents were noted compared to the control sites.

3.5. Changes in the properties of the materials with time

The research analysed the influences of time and environmental factors on the sorption capacity of the SAP in distilled water (Fig. 10). The maximum sorption capacity of the SAP model was approximately 270 g/g. The highest decrease in the sorption capacity of SAP was noted after the first year, reaching 72 %. After the subsequent year, no such dynamic changes were observed in the substrate, and the decrease was approximately 75 % compared with the model. After three years, the SAP retained only 17 % of its original sorption capacity.

Photographic documentation and organoleptic analyses allowed us to draw some preliminary conclusions about the BioWAG conditions. The best results were noted for seamed nonwovens, which demonstrated appropriate mechanical properties for at least two vegetation seasons. After the first season, discoloration and mass decreases were noted, but the nonwovens remained consistent. The degradation of needle-punched nonwovens was much faster as they lost their consistency after the first vegetation season (Fig. 11). However, the condition of the nonwovens at these sites did not have a negative influence on the further functioning of BioWAGs in the environment, as noted by their high efficiency in subsequent seasons. More parameters of the nonwovens are described in Marczak et al. (2020a).

4. Discussion

This study analysed several parameters that determine the influence of biodegradable water storage technology of WAGs on plant vegetation. With observations and measurements conducted for three vegetation seasons, the efficiency and environmental impact of this technology were comprehensively assessed. Five types of BioWAGs produced from plant and animal waste materials were tested under field conditions. BioWAG application had a positive influence on the biometric parameters of the grass, regardless of the variant used. At sites where BioWAGs were installed, noticeably higher increases in the fresh and dry weights of both the aboveground parts of the plants and the root systems were noted for the three vegetation seasons. Apart from that, this technology had a positive influence on other biometric parameters of plants. BioWAGs are subjected to gradual biodegradation, which is accompanied by the release of nutrients into the soil.

4.1. Assessment of plant material

SAP application is a well-known and successful method for combating the effects of adverse soil and climate conditions (Elshafie and Camele,

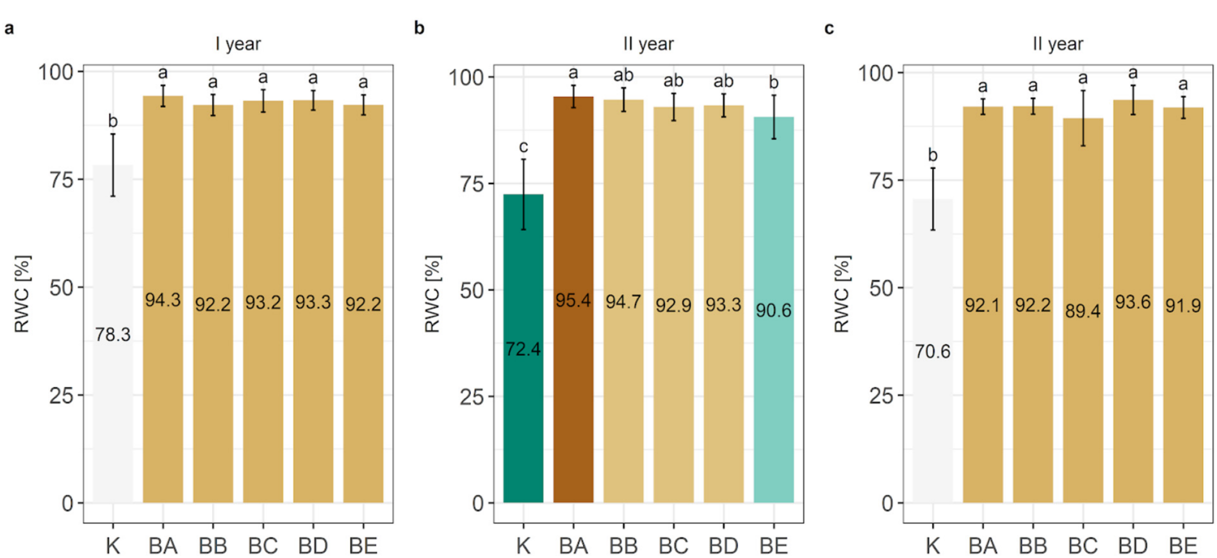


Fig. 7. Average values of the RWC indicator in the years 2018–2020. Error bars indicate the standard deviation (SD); Values indicated by the same letter are not significantly different (a = 0.05).

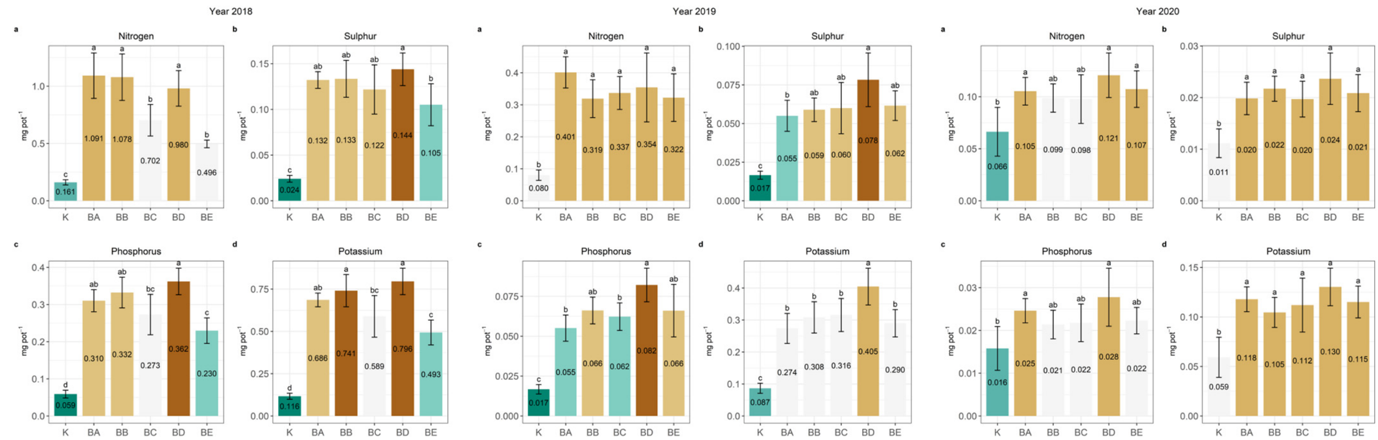


Fig. 8. Uptake of selected macronutrients by plants in the years 2018–2020. Error bars indicate the standard deviation (SD); Values indicated by the same letter are not significantly different (a = 0.05).

Fig. 9. Particle size distribution of soil used in the experiment.

2021; Wei and Durian, 2014). Numerous studies have described the benefits of using SAPs in agriculture and horticulture, where they have contributed to the reduction in water stress, increased yields, and the improvement of biometric parameters (Coello et al., 2018; Varela et al., 2016; Yang et al., 2019). Our results confirm the positive influence of SAPs on plant crops and biometric parameters. Moreover, our analyses demonstrated that the application of hydrogels in the form of a geocomposite brings many more benefits than the traditional methods of application by mixing them directly with soil. Tao et al. (2018) In their assessment of the efficiency of SAP, Tao et al. (2018) found that adding hydrogel directly to the substrate had a positive influence on the length of roots, shoots, and the growth of biomass during the first stages of maize development. The application of SAP resulted in a multi-fold increase in the aboveground and underground biomass of maize sprouts compared with the control site. Egrinya Eneji et al. (2013) assessed SAP potential at three irrigation levels, finding that SAP application increased the maize biomass by nearly 100 % under deficit irrigation and by 40 % under moderate irrigation. However, Rodionov et al. (2012) conducted a two-year field experiment, in which they analysed the influence of hydrogel mixed with additives on the development of *Dactylis glomerata* L. Depending on the variant used, an approximate 90 % increase in the growth of the aboveground parts of plants was noted after the first year of the experiment, but no significant differences were found in the development of the root system. After the second year, no differences were noted in the growth of aboveground biomass, whereas the increase in dry mass of the root system was

Table 4
Basic properties of the soils used for study.

Properties	Loamy sand
pH [KCl 1 M/dm^3]	6.20 ± 0.06
N [g/kg soil]	0.53 ± 0.01
P [mg/100 g soil]	18.90 ± 0.56
K [mg/100 g soil]	5.6 0 ± 0.22
Mg [mg/100 g soil]	1.90 ± 0.04
Mn [mg/kg soil]	13.00 ± 0.39
Cu [mg/kg soil]	0.70 ± 0.02
Fe [mg/kg soil]	167.80 ± 5.43
Zn [mg/kg soil]	1.60 ± 0.04
Specific Weight [g/cm^3]	2.65
Bulk Density [g/cm^3]	1.65
Porosity [−]	0.38
Soil organic matter (SOM) [%]	2.93
Electric Conductivity (EC) [μS/cm] (Śpitalniak et al., 2021)	123.00
Cation Exchange Capacity (CEC) [cmol(+)/kg] (Śpitalniak et al., 2021)	32.80

Table 5
Properties of control soil and soil after three vegetation seasons. The table presents the average values and the standard deviation (SD); Values indicated by the same letter are not significantly different (a = 0.05).

Signs	pH	N	P	K	Mg	Mn	Cu	Fe	Zn
	KCl 1 M/dm^3	g/kg soil	mg/100 g soil			mg/kg soil			
K	6.2 ± 0.06 a	0.525 ± 0.01 c	18.9 ± 0.56 a	5.6 ± 0.22 b	1.9 ± 0.04 a	13.0 ± 0.39 a	0.7 ± 0.02 a	167.8 ± 5.43 a	1.6 ± 0.04 a
BA	6.2 ± 0.03 a	0.894 ± 0.02 a	18.7 ± 0.69 a	10.1 ± 1.02 a	2.3 ± 0.37 a	9.6 ± 0.19 b	0.7 ± 0.05 a	136.5 ± 9.91 b	1.3 ± 0.21 ab
BB	6.2 ± 0.03 a	0.798 ± 0.04 a	19.2 ± 0.30 a	7.6 ± 0.67 ab	2.2 ± 0.22 a	9.9 ± 0.08 b	0.7 ± 0.04 a	146.6 ± 5.56 ab	1.3 ± 0.11 ab
BC	6.2 ± 0.07 a	0.689 ± 0.04 b	18.1 ± 0.67 a	7.8 ± 0.45 ab	2.2 ± 0.17 a	9.8 ± 0.57 b	0.7 ± 0.03 a	148.6 ± 5.26 ab	1.3 ± 0.11 ab
BD	6.2 ± 0.09 a	0.658 ± 0.02 b	18.7 ± 0.64 a	7.0 ± 0.32 b	2.1 ± 0.12 a	9.9 ± 1.01 b	0.7 ± 0.02 a	144.4 ± 4.34 ab	1.4 ± 0.06 ab
BE	6.4 ± 0.03 a	0.602 ± 0.03 bc	16.8 ± 0.12 a	7.3 ± 0.68 ab	1.7 ± 0.13 a	8.0 ± 0.25 b	0.5 ± 0.02 a	123.6 ± 3.39 b	0.9 ± 0.08 b

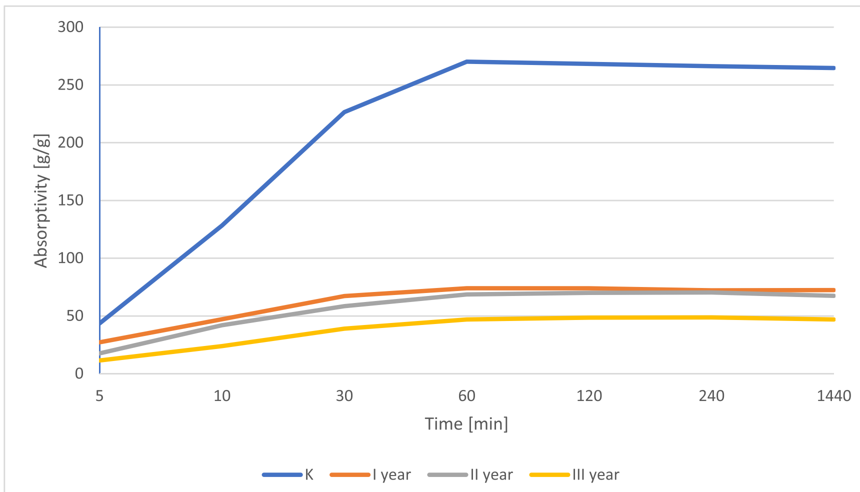


Fig. 10. SAP absorption in distilled water (20 °C).

approximately 65 % higher than that of the control site. Notably, SAP application inside a BioWAG resulted in a biomass growth increase of 430 % in the first year of the experiment, compared to the control. BioWAGs provided a source of nutrients and water storage, which was particularly noticeable during long water deficits. The grass on sites with BioWAGs applied remained in good condition, regardless of rainfall and temperature, as opposed to the control sites. Moreover, the root system of the grass was very well developed; it formed a dense and cohesive structure, and its mass was 130–220 % higher than that of the control plants after the first year of the experiment. Such a well-developed root system is crucial to the effective reinforcement of engineering objects, which limits the consequences of erosion and prevents the loss of stability. Additionally, a healthy root system contributed to the proper development of plants in subsequent seasons. Nemeskéri and Helyes (2019) also found that well-developed, long, and thick roots intensively foster the use of available water and contribute to the optimum development of aboveground parts. The high BioWAG efficiency in comparison to the traditional method of applying SAPs directly to the soil results from the combination of the retention capacity of SAPs with biodegradable waste materials, whose properties have been described in the literature.

Waste wool, which is the primary nonwoven material used in BioWAGs, is an animal fibre that is rich in easily accessible nutrients. When recycled in soil, it creates a natural fertiliser (Sharma et al., 2019). In this study, positive results were noted for the application of wool-based nonwovens. The sites with the highest share of wool in their BioWAG compositions were characterised by the highest biomass increases. The largest differences

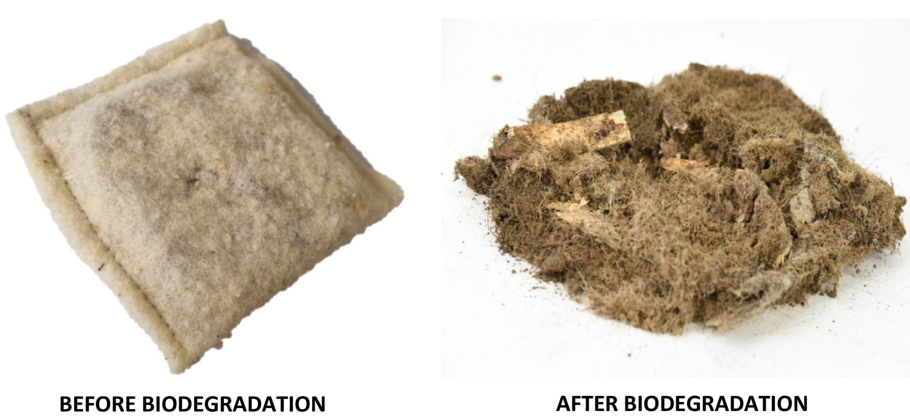


Fig. 11. Overview of the condition of needle-punched nonwovens before and after biodegradation (I year).

between the effects of using various types of BioWAGs were noted in the first season, when the used materials underwent an intensive biodegradation process. During the second vegetation season, differences in the effectiveness of the different variants were lower, which may have resulted from the gradual stabilisation of the biodegradation process at specific sites and that most of the nutrients had already been released into the substrate. The differences between specific sites were lowest in the third vegetation season, and the remaining efficiency of BioWAGs depended mainly on constant access to water. Additionally, Lal et al. (2020) noted the effectiveness of wool in field applications and observed noticeable improvements in soil fertility (by approximately 30 %) and enzyme activity (by approximately 10–30 %). Wool-based fertiliser resulted in an increase in the crops and dry mass of barley by approximately 50 % compared to the control group. This treatment improved the water use capacities of the plants. The high effectiveness of wool in field applications is due to its composition. Wool fibres contain carbon (50 %), nitrogen (15 %), sulphur (5 %), copper, iron, manganese, and zinc, which are essential plant nutrients. As a result of the wool biodegradation, these elements are gradually released into the soil, so they act as slow-release fertilisers while being environmentally safe (Lal et al., 2020). Broda (2019) also noted a positive influence of wool on the development of grass that forms the biotechnical protection of a slope. On sites enriched with wool, the grass formed a dense, tall, and intensely green turf cover.

4.2. The relative water content indicator

Plants are constantly exposed to the influence of factors that are referred to as stressors. Biotic stressors are living elements of the ecosystem as pathogens or pests. The main abiotic stressors include atmospheric conditions, such as too high or too low temperatures, droughts, or soaking (Chen et al., 2021; Mofini et al., 2022; Shao et al., n.d.). Currently, one of the main environmental problems is the limited access to water, which is necessary for the proper development of plants (Zaki and Radwan, 2022; Zhang et al., 2018). The RWC in plants is an indicator that determines the capacity of a plant to survive difficult conditions. Ahmad et al. (2022) noted a decrease in RWC values by approximately 23–25 % in maize leaves because of drought-induced stress. In another study on the influence of drought on wheat cultivation, Ahmad et al. (2021) observed a decrease in RWC by approximately 20 %. Such a significant reduction in RWC values indicates the stress caused by drought. Drought has an indispensable influence on crops, and its scale is higher than the annual crop loss caused by other abiotic stressors worldwide (Sun et al., 2021). Thus, limiting the effects of stress caused by water deficits is essential for maintaining the proper physiology and biochemistry of plants, and it influences the proper course of photosynthesis, protein synthesis, and hormonal balance (Zhang et al., 2013). BioWAGs, which significantly reduced the stress resulting from limited access to water in a three-year field experiment, provide a response to this challenge. These findings are confirmed by the fact that the RWC values remained 30 % higher than those on the control sites throughout the three vegetation seasons.

4.3. Analysis of the chemical composition of plants and soil properties

Numerous researchers have described the positive influence of natural soil additives on the availability of soil nutrients (Bhattacharyya et al., 2007; González-Coloma et al., 2022; Kulczycki and Sacała, 2020; Medyńska-Juraszek et al., 2021; Pandit et al., 2018; Shang et al., 2020). Our research confirms these observations, as BioWAGs significantly increased the uptake of selected macronutrients by grasses, which primarily resulted from the application of biodegradable materials. The presence of a biodegradable additive led to increased nitrogen uptake throughout the three vegetation seasons. In the first season, the uptake was over 510 % higher than that at the control sites. Such large differences were directly linked to the increased biomass growth at all the sites equipped with BioWAGs. Wool, which is the main component of biocomposites, consists of 95 % keratin and is a valuable source of nitrogen. Parlato and Porto (2020) found that 1 kg of wool may contain even up to 0.25 kg of nitrogen and 0.03 kg of sulphur (Gillespie et al., 2021). Bhavsar et al. (2021), who analysed wool-based biocomposites, observed that nutrients that were easily accessible to plants were released into the substrate. Similar findings concerning the composition and properties of wool were noted by Broda (2019), who found that wool applied in the form of ropes on test embankments had a positive influence on plant growth. The organic nitrogen content increased by 400 % immediately after wool addition. Over time, a gradual decrease in the concentration of organic N was noted as it was transformed into forms accessible to plants. The gradual release of nutrients into the soil resulted in intensive grass development on the test slope. Our results also demonstrated that regardless of the variant applied, BioWAGs provided the plants with accessible forms of N, S, P, and K, which had a positive influence on their development and overall condition. Nitrogen is an essential element for plant nutrition, as it fosters the proper plant development, including the growth of aboveground parts of the root system and the green colour of the stems, shoots, and leaves (Lei et al., 2022; Sun et al., 2014; Yang et al., 2022a). Sulphur performs metabolic functions and improves plant resistance to abiotic and biotic stresses (Kulczycki and Sacała, 2020). Phosphorus and potassium are also crucial for proper development and functioning of the root system and proper water management (Yugandhar et al., 2022; Zhang et al., 2022).

4.4. Changes in the properties of SAP and nonwovens

SAPs are particularly important in agriculture and horticulture, where their task is to improve the retention capacity of soils (Das and Ghosh, 2022; Hüttermann et al., 2009; Zhang et al., 2021). However, there are numerous factors that may limit water storage capacity, such as soil pressure, salination, temperature, soil pH, the presence of univalent or multivalent ions, and soil microorganisms (Guezennec et al., 2014; Lejcuś et al., 2015a; Nascimento et al., 2021). The application of an internal skeleton structure in BioWAG reduced the negative impact of the pressure. Nevertheless, our results reveal a noticeable decrease in the sorption capacity of SAPs after the first vegetation season. It then deepened through the subsequent vegetation seasons. Such a rapid decrease in the sorption capacity after the first season may have resulted from the use of tap water, which contains bi- and tri-valent ions, during application and the subsequent influence of the soil solution. The decreased sorption capacity may have also been caused by gradual biodegradation in the soil. Certain soil bacteria uses a copolymer of acrylamide and potassium acrylate as a source of nitrogen or carbon (Guezennec et al., 2014). Matsuoka et al. (2002) showed that selected soil bacteria (*Bacillus sphaericus* and *Acinetobacter*) may reduce the concentration of polyacrylamide by 16–19 %. Guezennec et al. (2014) also described the possibility of SAP degradation by other bacteria such as *Enterococcus faecalis*, *Geobacillus thermoglucosidasius*, *Klebsiella pneumoniae*, *Variovorax boronicumulans*, and *Kluyvera georgiana*. Oksińska et al. (2016) noted, in a nine-month pot experiment, a 35 % decrease in the sorption capacity and a loss of over 30 % of the dry weight of the copolymer of acrylamide and potassium acrylate applied in the synthetic versions of geocomposites, which suggested that it had decomposed gradually. Furthermore, it was found that certain bacteria that are naturally present in the soil may degrade SAP.

Needle-punched nonwovens underwent intensive biodegradation during the first vegetation season, which fostered vegetation at that time. The wool biodegradation process depends on its quality and environmental factors. As a result of biodegradation, wool husks become damaged, which increased the vulnerability of the core cells to microbiological degradation (Broda, 2019; Korniłłowicz-Kowalska and Bohacz, 2011). In studies on the biodegradation of biocomposites based on waste wool and sulphur pulp, Bhavsar et al. (2021) observed intense biodegradation in the first months following its application to the soil. After three months of operation, a loss of integrity was noted, and the structure of both wool fibres and the sulphur pulp had been destroyed. However, plant fibres, such as jute or linen, are often characterised by longer degradation times and good strength properties. Linen has a high tensile strength, which increases under the influence of moisture, making it an attractive additive in the production of nonwovens (Abiola, 2017; Yun et al., 2022). Jute is also characterised by good strength parameters, as the addition of jute fibres improves the strength and elasticity of the fabric (Hasanuzzaman et al., 2021; Saleem et al., 2020; Zhang et al., 2019). Our findings also demonstrate that the degradation time of nonwovens with the addition of plant-based fibres was prolonged. BioWAGs in which a mix of wool and jute was applied had the longest biodegradation time.

5. Conclusions

Globally, there have been attempts to develop innovative strategies and technologies to protect plants against climate change, the effects of drought, and the loss of soil fertility. This study presents the effects of the practical application of an innovative technology to retain water in soil in the form of BioWAGs. The application of BioWAGs significantly improved grass growth during the three-year field experiment. BioWAGs caused a multi-fold increase in the biomass of the aboveground and belowground parts of the plants and had a positive influence on other biometric parameters. Moreover, the water stored inside the BioWAGs eliminated the effects of water stress, as proven by the high RWC indices throughout the experiment.

The results demonstrated that the application of biodegradable waste fibres plays an important role in supplying nutrients to plants. Owing to the gradual biodegradation of fibres, the BioWAGs released nutrients to the soil gradually over the entire three-year period, and their effects may be compared to those of slow-release fertilisers. The application of BioWAGs increased the growth of the aboveground parts of the plants by 40–430 % compared to the control group. The highest effectiveness was noted in the first and second years after application. In the context of a circular economy, reusing waste wool may help to reduce both energy consumption and environmental pollution. The recycling of wool and other waste fibres offers an opportunity to manufacture innovative materials that are fully compliant with user expectations and environmental needs. Economically, the wide availability and low cost of natural fibres enables the wide-scale production of soil additives and reduces the need for more expensive synthetic materials. Moreover, another reason that supports the use of waste fibres is the need to limit climate change. The application of waste materials enables an increase in carbon sequestration in the soil and closed-loop fertilisation is an efficient form of recycling. The presented results provide a basis for introducing a solution that reduces the amount of irrigation and fertilisation while simultaneously fulfilling the objectives of a circular economy and the principles of sustainable development on a wide scale.

CRediT authorship contribution statement

Daria Marczak: conceptualization, investigations, methodology, writing- original draft preparation, resources, formal analysis, data curation, application of statistical, visualization.

Krzysztof Lejcuś: writing- reviewing and editing, funding acquisition.

Grzegorz Kulczycki: investigation, application of statistical.

Jakub Misiewicz: visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Research was conducted as part of the interdisciplinary project "Hydrobox2.0, an innovative technology supporting water saving and plant growth." POIR.04.01.04-00-0061/16 was carried out under the Operational Programme Smart Growth Operational Programme co-financed by the European Union from the European Regional Development Fund.

The APC/BPC is financed/co-financed by Wroclaw University of Environmental and Life Sciences.

"*The authors used meteorological data from the Faculty Agricultural and Hydrological Observatory Wrocław-Swojec (WOAiHW-S)*."

References

Abiola, O.S., 2017. Natural fibre cement composites. In: Fan, Mizi, Fu, Feng (Eds.), Advanced High Strength Natural Fibre Composites in Construction. Elsevier, pp. 205–214 https://doi.org/10.1016/B978-0-08-100411-1.00008-X.

Adediran, J.A., De Baets, N., Kiekens, L., Mnkeni, P.N.S., Muyima, N.Y.O., Thys, A., 2012. Organic Waste Materials for Soil Fertility Improvement in the Border Region of the Eastern Cape, South Africa. 20, pp. 283–300. https://doi.org/10.1080/01448765.2003.9754974.

Ahmad, A., Aslam Id, Z., Naz Id, M., Hussain Id, S., Javed Id, T., Aslam, S., Razaid, A., Aliid, H.M., Siddiqui, M.H., Salemid, M.Z.M., Hano, C., Shabbirid, R., Ahmar, S., Saeed, T., Jamal, M.A., 2021. Exogenous salicylic acid-induced drought stress tolerance in wheat (Triticum aestivum L.) grown under hydroponic culture. PLoS One 16, e0260556. https://doi.org/10.1371/JOURNAL.PONE.0260556.

Ahmad, S., Wang, G.Y., Muhammad, I., Farooq, S., Kamran, M., Ahmad, I., Zeeshan, M., Javed, T., Ullah, S., Huang, J.H., Zhou, X.B., 2022. Application of melatonin-mediated modulation of drought tolerance by regulating photosynthetic efficiency, chloroplast ultrastructure, and endogenous hormones in maize. Chem. Biol. Technol. Agric. 91 (9), 1–14. https://doi.org/10.1186/S40538-021-00272-1.

Al Faruque, M.A., Remadevi, R., Guirguis, A., Kiziltas, A., Mielewski, D., Naebe, M., 2021. Graphene oxide incorporated waste wool/PAN hybrid fibres. Sci. Rep. 11. https://doi.org/10.1038/S41598-021-91561-0.

An, C., Sun, C., Li, N., Huang, B., Jiang, J., Shen, Y., Wang, Chong, Zhao, X., Cui, B., Wang, Chunxin, Li, X., Zhan, S., Gao, F., Zeng, Z., Cui, H., Wang, Y., 2022. Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture. J. Nanobiotechnology 201 (20), 1–19. https://doi.org/10.1186/S12951-021-01214-7.

Anagnostopoulou, K., Nannou, C., Evgenidou, E., Lambropoulou, D., 2022. Overarching issues on relevant pesticide transformation products in the aquatic environment: a review. Sci. Total Environ. 815, 152863. https://doi.org/10.1016/J.SCITOTENV.2021.152863.

Arican, F., Uzuner-Demir, A., Sancakli, A., Ismar, E., 2021. Synthesis and characterization of superabsorbent hydrogels from waste bovine hair via keratin hydrolysate graft with acrylic acid (AA) and acrylamide (AAm). Chem. Pap. 75, 6601–6610. https://doi.org/10.1007/S11696-021-01828-Z/FIGURES/7.

Bąbelewski, P., Pancerz, M., Dębicz, R., 2017. The influence of geocomposites on the biomass production, the nutritional status of plants and the substrate characteristics in the container nursery production of rosa cv. white meidiland and Berberis thunbergii cv. green carpet. J. Elem. 22, 1095–1106. https://doi.org/10.5601/jelem.2016.21.3.1144.

Baghbanzadeh, M., Rana, D., Lan, C.Q., Matsuura, T., 2017. Zero thermal input membrane distillation, a zero-waste and sustainable solution for freshwater shortage. Appl. Energy 187, 910–928. https://doi.org/10.1016/J.APENERGY.2016.10.142.

Bhattacharyya, R., Chandra, S., Singh, R.D., Kundu, S., Srivastva, A.K., Gupta, H.S., 2007. Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat–soybean rotation. Soil Tillage Res. 94, 386–396. https://doi.org/10.1016/J.STILL.2006.08.014.

Bhavsar, P., Balan, T., Fontana, G.D., Zoccola, M., Patrucco, A., Tonin, C., 2021. Sustainably processed waste wool fiber-reinforced biocomposites for agriculture and packaging applications. Fibers 9, 55. https://doi.org/10.3390/FIB9090055.

Bisht, N., Chauhan, P.S., 2020. Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. Soil Contam. Threat. Sustain. Solut. https://doi.org/10.5772/INTECHOPEN.94593.

Bousshine, S., Ouakarrouch, M., Bybi, A., Laaroussi, N., Garoum, M., Tilioua, A., 2022. Acoustical and thermal characterization of sustainable materials derived from vegetable, agricultural, and animal fibers. Appl. Acoust. 187. https://doi.org/10.1016/J.APACOUST.2021.108520.

Bremner, J.M., 1960. Determination of nitrogen in soil by the kjeldahl method. J. Agric. Sci. 55, 11–33. https://doi.org/10.1017/S0021859600021572.

Broda, J., 2019. Biodegradation of sheep wool geotextiles designed for erosion control. Environmental Chemistry and Recent Pollution Control Approaches. IntechOpen https://doi.org/10.5772/intechopen.84334.

Broda, J., Mitka, A., Gawłowski, A., 2020. Greening of road slope reinforced with wool fibres. Mater. Today Proc. https://doi.org/10.1016/j.matpr.2020.01.249.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125. https://doi.org/10.1016/J.SOILBIO.2018.01.030.

Buzzard, V., Gil-Loaiza, J., Graf Grachet, N., Talkington, H., Youngerman, C., Tfaily, M.M., Meredith, L.K., 2021. Green infrastructure influences soil health: biological divergence one year after installation. Sci. Total Environ. 801, 149644. https://doi.org/10.1016/J.SCITOTENV.2021.149644.

Cao, L., Zhang, D., Fang, Q., Yu, L., 2020. Movements of ground and existing structures induced by slurry pressure-balance tunnel boring machine (SPB TBM) tunnelling in clay. Tunn. Undergr. Sp. Technol. 97, 103278. https://doi.org/10.1016/j.tust.2019.103278.

Carrão, H., Naumann, G., Barbosa, P., 2016. Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability. Glob. Environ. Chang. 39, 108–124. https://doi.org/10.1016/J.GLOENVCHA.2016.04.012.

Chaukura, N., Kefeni, K.K., Chikurunhe, I., Nyambiya, I., Gwenzi, W., Moyo, W., Nkambule, T.T.I., Mamba, B.B., Abulude, F.O., 2021. Microplastics in the aquatic environment—

the occurrence, sources, ecological impacts, fate, and remediation challenges. Pollut. 1, 95–118. https://doi.org/10.3390/POLLUTANTS1020009.

Chehade, G., Dincer, I., 2021. Progress in green ammonia production as potential carbon-free fuel. Fuel 299, 120845. https://doi.org/10.1016/J.FUEL.2021.120845.

Chen, J., Zhao, X., Li, Yuqiang, Luo, Y., Zhang, Y., Liu, M., Li, Yan, 2021. Physiological responses of Agriophyllum squarrosum and Setaria viridis to drought and re-watering. Sci. Reports 111 (11), 1–10. https://doi.org/10.1038/s41598-021-98246-8.

Coello, J., Ameztegui, A., Rovira, P., Fuentes, C., Piqué, M., 2018. Innovative soil conditioners and mulches for forest restoration in semiarid conditions in Northeast Spain. Ecol. Eng. 118, 52–65. https://doi.org/10.1016/J.ECOLENG.2018.04.015.

Corscadden, K.W., Biggs, J.N., Stiles, D.K., 2014. Sheep's wool insulation: a sustainable alternative use for a renewable resource? Resour. Conserv. Recycl. 86, 9–15. https://doi.org/10.1016/j.resconrec.2014.01.004.

Coskun, D., Britto, D.T., Shi, W., Kronzucker, H.J., 2017. Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nat. Plants 36 (3), 1–10. https://doi.org/10.1038/nplants.2017.74.

Cybulak, M., Sokołowska, Z., Boguta, P., 2021. The influence of biochar on the content of carbon and the chemical transformations of fallow and grassland humic acids. Sci. Reports 111 (11), 1–14. https://doi.org/10.1038/s41598-021-85239-w.

Czuba, K., Bastrzyk, A., Rogowska, A., Janiak, K., Pacyna, K., Kossińska, N., Kita, M., Chrobot, P., Podstawczyk, D., 2021. Towards the circular economy — a pilot-scale membrane technology for the recovery of water and nutrients from secondary effluent. Sci. Total Environ. 791, 148266. https://doi.org/10.1016/J.SCITOTENV.2021.148266.

Dan, Z., Guoli, W., Huicheng, Z., 2011. Assessment on agricultural drought risk based on variable fuzzy sets model. Chin. Geogr. Sci. 212 (21), 167–175. https://doi.org/10.1007/S11769-011-0456-2.

Das, S.K., Ghosh, G.K., 2022. Hydrogel-biochar composite for agricultural applications and controlled release fertilizer: a step towards pollution free environment. Energy 242, 122977. https://doi.org/10.1016/J.ENERGY.2021.122977.

Das, O., Babu, K., Shanmugam, V., Sykam, K., Tebyetekerwa, M., Neisiany, R.E., Försth, M., Sas, G., Gonzalez-Libreros, J., Capezza, A.J., Hedenqvist, M.S., Berto, F., Ramakrishna, S., 2022. Natural and industrial wastes for sustainable and renewable polymer composites. Renew. Sust. Energ. Rev. 158, 112054. https://doi.org/10.1016/J.RSER.2021.112054.

Deák, B., Bede, Á., Rádai, Z., Tóthmérész, B., Török, P., Nagy, D., Torma, A., Lőrinczi, G., Nagy, A., Mizser, S., Kelemen, A., Valkó, O., 2021. Different extinction debts among plants and arthropods after loss of grassland amount and connectivity. Biol. Conserv. 264, 109372. https://doi.org/10.1016/J.BIOCON.2021.109372.

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., Zheng, B., 2016. Biochar to improve soil fertility. A review. Agron. Sustain. Dev. 362 (36), 1–18. https://doi.org/10.1007/S13593-016-0372-Z.

Du, H., Huang, S., Wang, J., 2022. Environmental risks of polymer materials from disposable face masks linked to the COVID-19 pandemic. Sci. Total Environ. 815, 152980. https://doi.org/10.1016/J.SCITOTENV.2022.152980.

Egrinya Eneji, A., Islam, R., An, P., Amalu, U.C., 2013. Nitrate retention and physiological adjustment of maize to soil amendment with superabsorbent polymers. J. Clean. Prod. 52, 474–480. https://doi.org/10.1016/J.JCLEPRO.2013.02.027.

El-mrini, S., Aboutayeb, R., Zouhri, A., 2022. Effect of initial C/N ratio and turning frequency on quality of final compost of turkey manure and olive pomace. J. Eng. Appl. Sci. 691 (69), 1–20. https://doi.org/10.1186/S44147-022-00092-6.

Elshafie, H.S., Camele, I., 2021. Applications of absorbent polymers for sustainable plant protection and crop yield. Sustain. 13, 3253. https://doi.org/10.3390/SU13063253.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. Nat. Geosci. 110 (1), 636–639. https://doi.org/10.1038/ngeo325.

Fang, J., Meng, C., Zhang, G., 2022. Agricultural waste of Ipomoea batatas leaves as a source of natural dye for green coloration and bio-functional finishing for textile fabrics. Ind. Crop. Prod. 177, 114440. https://doi.org/10.1016/J.INDCROP.2021.114440.

Faraca, G., Astrup, T., 2019. Plastic waste from recycling centres: characterisation and evaluation of plastic recyclability. Waste Manag. 95, 388–398. https://doi.org/10.1016/J.WASMAN.2019.06.038.

Fulton, J., 1999. Using science to advocate action on climate change. Ecosyst. Heal. 5, 110–117. https://doi.org/10.1046/J.1526-0992.1999.09916.X.

Gatta, G.D., Lotti, P., 2019. Systematics, crystal structures, and occurrences of zeolites. Modif. Clay Zeolite Nanocompos. Mater. Environ. Pharm. Appl, 1–25. https://doi.org/10.1016/B978-0-12-814617-0.00001-3.

Gillespie, G.D., Dada, O., McDonnell, K.P., 2021. The potential for hydrolysed sheep wool as a sustainable source of fertiliser for Irish agriculture. Sustain. 14, 365. https://doi.org/10.3390/SU14010365 2022.

González-Coloma, A., Andrés, M.F., Francisco Quílez Del Moral, J., Diaz, C.E., Rusli, L.S., Abdullah, R., Yaacob, J.S., Osman, N., 2022. Organic amendments effects on nutrient uptake, secondary metabolites, and antioxidant properties of Melastoma malabathricum L. Plants 11, 153. https://doi.org/10.3390/PLANTS11020153.

Good, A.G., Beatty, P.H., 2011. Fertilizing nature: a tragedy of excess in the commons. PLoS Biol. 9. https://doi.org/10.1371/JOURNAL.PBIO.1001124.

Guezennec, A.G., Michel, C., Bru, K., Touze, S., Desroche, N., Mnif, I., Motelica-Heino, M., 2014. Transfer and degradation of polyacrylamide-based flocculants in hydrosystems: a review. Environ. Sci. Pollut. Res. 229 (22), 6390–6406. https://doi.org/10.1007/S11356-014-3556-6.

Guo, J.J., Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W., Li, H., Cai, Q.Y., Mo, C.H., Wong, M.H., 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137, 105263. https://doi.org/10.1016/J.ENVINT.2019.105263.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 344, 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014.

Hanson, P.J., Weltzin, J.F., 2000. Drought disturbance from climate change: response of United States forests. Sci. Total Environ. 262, 205–220. https://doi.org/10.1016/S0048-9697(00)00523-4.

Hasanuzzaman, M., Rakib, M., Raihan, H., Khojah, E., Samra, B.N., Fujita, M., Nahar, K., 2021. Biochar and chitosan regulate antioxidant defense and methylglyoxal detoxification systems and enhance salt tolerance in jute (Corchorus olitorius L.). Antioxidants 10, 2017. https://doi.org/10.3390/ANTIOX10122017.

Hou, D., Bolan, N.S., Tsang, D.C.W., Kirkham, M.B., O'Connor, D., 2020. Sustainable soil use and management: an interdisciplinary and systematic approach. Sci. Total Environ. 729, 138961. https://doi.org/10.1016/J.SCITOTENV.2020.138961.

Hüttermann, A., Orikiriza, L.J.B., Agaba, H., 2009. Application of superabsorbent polymers for improving the ecological chemistry of degraded or polluted lands. CLEAN SoilAir Water 37, 517–526. https://doi.org/10.1002/CLEN.200900048.

Igalavithana, A.D., Ok, Y.S., Usman, A.R.A., Al-Wabel, M.I., Oleszczuk, P., Lee, S.S., 2015. The Effects of Biochar Amendment on Soil Fertility, pp. 123–144 https://doi.org/10.2136/SSSASPECPUB63.2014.0040.

Jatav, H.S., Rajput, V.D., Minkina, T., Singh, S.K., Chejara, S., Gorovtsov, A., Barakhov, A., Bauer, T., Sushkova, S., Mandzieva, S., Burachevskaya, M., Kalinitchenko, V.P., 2021. Sustainable approach and safe use of biochar and its possible consequences. Sustain. 13, 10362. https://doi.org/10.3390/SU131810362.

Jury, W.A., Vaux, H.J., 2007. The emerging global water crisis: managing scarcity and conflict between water users. Adv. Agron. 95, 1–76. https://doi.org/10.1016/S0065-2113(07)95001-4.

Katare, Y., Singh, P., Singh Sankhla, M., Singhal, M., Jadhav, E.B., Parihar, K., Nikalje, B.T., Trpathi, A., Bhardwaj, L., 2022. Microplastics in aquatic environments: sources, ecotoxicity, detection & remediation. Review 12, 3407–3428. https://doi.org/10.33263/BRIAC123.34073428.

Kayastha, V., Patel, J., Kathrani, N., Varjani, S., Bilal, M., Show, P.L., Kim, S.-H., Bontempi, E., Bhatia, S.K., Bui, X.-T., 2022. New insights in factors affecting ground water quality with focus on health risk assessment and remediation techniques. Environ. Res. 212, 113171. https://doi.org/10.1016/J.ENVRES.2022.113171.

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. Environ. Int. 132, 105078. https://doi.org/10.1016/J.ENVINT.2019.105078.

Korniłłowicz-Kowalska, T., Bohacz, J., 2011. Biodegradation of keratin waste: theory and practical aspects. Waste Manag. 31, 1689–1701. https://doi.org/10.1016/j.wasman.2011.03.024.

Kulczycki, G., Sacała, E., 2020. Sulfur application alleviates chromium stress in maize and wheat. Open Chem. 18, 1093–1104. https://doi.org/10.1515/CHEM-2020-0155/MACHINEREADABLECITATION/RIS.

Lal, B., Sharma, S.C., Meena, R.L., Sarkar, S., Sahoo, A., Balai, R.C., Gautam, P., Meena, B.P., 2020. Utilization of byproducts of sheep farming as organic fertilizer for improving soil health and productivity of barley forage. J. Environ. Manag. 269, 110765. https://doi.org/10.1016/j.jenvman.2020.110765.

Lei, B., Chang, W., Zhao, H., Zhang, K., Yu, J., Yu, S., Cai, K., Zhang, J., Lu, K., 2022. Nitrogen application and differences in leaf number retained after topping affect the tobacco (Nicotiana tabacum) transcriptome and metabolome. BMC Plant Biol. 22, 1–16. https://doi.org/10.1186/S12870-022-03426-X/FIGURES/8.

Lejcuś, K., Dąbrowska, J., Garlikowski, D., Śpitalniak, M., 2015a. The application of water-absorbing geocomposites to support plant growth on slopes. Geosynth. Int. 22, 452–456. https://doi.org/10.1680/jgein.15.00025.

Lejcuś, K., Dąbrowska, J., Garlikowski, D., Śpitalniak, M., 2015b. The application of water-absorbing geocomposites to support plant growth on slopes. Geosynth. Int. 22, 452–456. https://doi.org/10.1680/jgein.15.00025.

Lejcuś, K., Śpitalniak, M., Dabrowska, J., 2018. Swelling behaviour of superabsorbent polymers for soil amendment under different loads. Polymers (Basel). 10, 271. https://doi.org/10.3390/polym10030271.

Li, C., Feng, H., Luo, X., Li, Y., Wang, N., Wu, W., Zhang, T., Dong, Q., Siddique, K.H.M., 2022. Limited irrigation and fertilization in sand-layered soil increases nitrogen use efficiency and economic benefits under film mulched ridge-furrow irrigation in arid areas. Agric. Water Manag. 262, 107406. https://doi.org/10.1016/J.AGWAT.2021.107406.

Li, L., Hao, Y., Zheng, Z., Wang, W., Biederman, J.A., Wang, Y., Wen, F., Qian, R., Xu, C., Zhang, B., Song, X., Cui, X., Xu, Z., 2022. Heavy rainfall in peak growing season had larger effects on soil nitrogen flux and pool than in the late season in a semiarid grassland. Agric. Ecosyst. Environ. 326, 107785. https://doi.org/10.1016/J.AGEE.2021.107785.

Li, X., Li, B., Chen, L., Liang, J., Huang, R., Tang, X., Zhang, X., Wang, C., 2022. Partial substitution of chemical fertilizer with organic fertilizer over seven years increases yields and restores soil bacterial community diversity in wheat–rice rotation. Eur. J. Agron. 133, 126445. https://doi.org/10.1016/J.EJA.2021.126445.

Manjaiah, K.M., Mukhopadhyay, R., Paul, R., Datta, S.C., Kumararaja, P., Sarkar, B., 2019. Clay minerals and zeolites for environmentally sustainable agriculture. Modif. Clay Zeolite Nanocompos. Mater. Environ. Pharm. Appl, 309–329. https://doi.org/10.1016/B978-0-12-814617-0.00008-6.

Marczak, D., Lejcuś, K., Grzybowska-Pietras, J., Biniaś, W., Lejcuś, I., Misiewicz, J., 2020a. Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation. Sustain. Mater. Technol. 26, e00235. https://doi.org/10.1016/J.SUSMAT.2020.E00235.

Marczak, D., Lejcuś, K., Misiewicz, J., 2020b. Characteristics of biodegradable textiles used in environmental engineering: a comprehensive review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.122129.

Marques, A.R., de Oliveira, Santiago, Patrício, P., Soares dos Santos, F., Monteiro, M.L., de Carvalho Urashima, D., de Souza Rodrigues, C., 2014. Effects of the climatic conditions of the southeastern Brazil on degradation the fibers of coir-geotextile: evaluation of mechanical and structural properties. Geotext. Geomembranes 42, 76–82. https://doi.org/10.1016/j.geotexmem.2013.07.004.

Matsuoka, H., Ishimura, F., Takeda, T., Hikuma, M., 2002. Isolation of polyacrylamide-degrading microorganisms from soil. Biotechnol. Bioprocess Eng. 75 (7), 327–330. https://doi.org/10.1007/BF02932844.

McLaughlin, S.P., 1985. Economic prospects for new crops in the Southwestern United States. Econ. Bot. 394 (39), 473–481. https://doi.org/10.1007/BF02858756.

Medyńska-Juraszek, A., Latawiec, A., Królczyk, J., Bogacz, A., Kawałko, D., Bednik, M., Dudek, M., 2021. Biochar improves maize growth but has a limited effect on soil properties: evidence from a three-year field experiment. Sustain. 13, 3617. https://doi.org/10.3390/su13073617.

Meza, I., Eyshi Rezaei, E., Siebert, S., Ghazaryan, G., Nouri, H., Dubovyk, O., Gerdener, H., Herbert, C., Kusche, J., Popat, E., Rhyner, J., Jordaan, A., Walz, Y., Hagenlocher, M., 2021. Drought risk for agricultural systems in South Africa: drivers, spatial patterns, and implications for drought risk management. Sci. Total Environ. 799, 149505. https://doi.org/10.1016/J.SCITOTENV.2021.149505.

Mi, J., Gregorich, E.G., Xu, S., McLaughlin, N.B., Ma, B., Liu, J., 2017. Effect of bentonite amendment on soil hydraulic parameters and millet crop performance in a semi-arid region. F. Crop. Res. 212, 107–114. https://doi.org/10.1016/J.FCR.2017.07.009.

Miljković, V., Gajić, I., Nikolić, L., 2021. Waste materials as a resource for production of CMC superabsorbent hydrogel for sustainable agriculture. Polym. 13, 4115. https://doi.org/10.3390/POLYM13234115.

Misiewicz, J., Lejcuś, K., Dąbrowska, J., Marczak, D., 2019a. The characteristics of absorbency under load (AUL) for superabsorbent and soil mixtures. Sci. Rep. 9, 18098. https://doi.org/10.1038/s41598-019-54744-4.

Misiewicz, J., Lejcuś, K., Dąbrowska, J., Marczak, D., 2019b. The characteristics of absorbency under load (AUL) for superabsorbent and soil mixtures. Sci. Rep. 9, 1–9. https://doi.org/10.1038/s41598-019-54744-4.

Mofini, M.-T., Diedhiou, A.G., Simonin, M., Dondjou, D.T., Pignoly, S., Ndiaye, C., Min, D., Vigouroux, Y., Laplaze, L., Kane, A., 2022. Cultivated and wild pearl millet display contrasting patterns of abundance and co-occurrence in their root mycobiome. Sci. Reports 121 (12), 1–17. https://doi.org/10.1038/s41598-021-04097-8.

Myint, S.W., Aggarwal, R., Zheng, B., Wentz, E.A., Holway, J., Fan, C., Selover, N.J., Wang, C., Fischer, H.A., 2021. Adaptive crop management under climate uncertainty: changing the game for sustainable water use. Atmos. 12, 1080. https://doi.org/10.3390/ATMOS12081080.

Nascimento, C.D.V., Simmons, R.W., Costa, M.C.G., Feitosa, J.P.de A., Dias, C.T.dos S., 2021. Potential of superabsorbent hydrogels to improve agriculture under abiotic stresses. J. Arid Environ. 189, 104496. https://doi.org/10.1016/J.JARIDENV.2021.104496.

Nemeskéri, E., Helyes, L., 2019. Physiological responses of selected vegetable crop species to water stress. Agron. 9, 447. https://doi.org/10.3390/AGRONOMY9080447.

Nghiem, S., Tran, B., Afoakwah, C., Byrnes, J., Scuffham, P., 2021. Wealthy, healthy and green: are we there yet? World Dev. 147, 105628. https://doi.org/10.1016/J.WORLDDEV.2021.105628.

Nguyen, G., Grzybowska-Pietras, J., Broda, J., 2021. Application of innovative ropes from textile waste as an anti-erosion measure. Materials (Basel) 14, 1–16. https://doi.org/10.3390/ma14051179 †.

Ogunmakinde, O.E., Egbelakin, T., Sher, W., 2022. Contributions of the circular economy to the UN sustainable development goals through sustainable construction. Resour. Conserv. Recycl. 178, 106023. https://doi.org/10.1016/J.RESCONREC.2021.106023.

Oksińska, M.P., Magnucka, E.G., Lejcuś, K., Pietr, S.J., 2016. Biodegradation of the cross-linked copolymer of acrylamide and potassium acrylate by soil bacteria. Environ. Sci. Pollut. Res. 23, 5969–5977. https://doi.org/10.1007/s11356-016-6130-6.

Oksińska, M.P., Magnucka, E.G., Lejcuś, K., Jakubiak-Marcinkowska, A., Ronka, S., Trochimczuk, A.W., Pietr, S.J., 2019. Colonization and biodegradation of the cross-linked potassium polyacrylate component of water absorbing geocomposite by soil microorganisms. Appl. Soil Ecol. 133, 114–123. https://doi.org/10.1016/j.apsoil.2018.09.014.

Pandit, N.R., Mulder, J., Hale, S.E., Martinsen, V., Schmidt, H.P., Cornelissen, G., 2018. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input nepalese soil. Sci. Total Environ. 625, 1380–1389. https://doi.org/10.1016/J.SCITOTENV.2018.01.022.

Parlato, M.C.M., Porto, S.M.C., 2020. Organized framework of main possible applications of sheep wool fibers in building components. Sustain. 12, 76. https://doi.org/10.3390/SU12030761.

Platnieks, O., Gaidukovs, S., Kumar Thakur, V., Barkane, A., Beluns, S., 2021. Bio-based poly (butylene succinate): recent progress, challenges and future opportunities. Eur. Polym. J. 161, 110855. https://doi.org/10.1016/J.EURPOLYMJ.2021.110855.

Prambauer, M., Wendeler, C., Weitzenböck, J., Burgstaller, C., 2019. Biodegradable geotextiles – an overview of existing and potential materials. Geotext. Geomembr. 47, 48–59. https://doi.org/10.1016/j.geotexmem.2018.09.006.

Regni, L., Nasini, L., Ilarioni, L., Brunori, A., Massaccesi, L., Agnelli, A., Proietti, P., 2017. Long term amendment with fresh and composted solid olive mill waste on olive grove affects carbon sequestration by prunings, fruits, and soil. Front. Plant Sci. 7, 2042. https://doi.org/10.3389/FPLS.2016.02042/BIBTEX.

Roa, K., Oyarce, E., Boulett, A., ALSamman, M., Oyarzún, D., Pizarro, G.D.C., Sánchez, J., 2021. Lignocellulose-based materials and their application in the removal of dyes from water: a review. Sustain. Mater. Technol. 29, e00320. https://doi.org/10.1016/J.SUSMAT.2021.E00320.

Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H.K., Rios-Mendoza, L.M., Takada, H., Teh, S., Thompson, R.C., 2013. Classify plastic waste as hazardous. Nat. 4947436 (494), 169–171. https://doi.org/10.1038/494169a.

Rodionov, A., Nii-Annang, S., Bens, O., Trimborn, M., Schillem, S., Schneider, B.U., Raab, T., Hüttl, R.F., 2012. Impacts of soil additives on crop yield and C-sequestration in post mine substrates of Lusatia, Germany. Pedosphere 22, 343–350. https://doi.org/10.1016/S1002-0160(12)60021-6.

Saleem, M.H., Ali, S., Rehman, M., Hasanuzzaman, M., Rizwan, M., Irshad, S., Shafiq, F., Iqbal, M., Alharbi, B.M., Alnusaire, T.S., Qari, S.H., 2020. Jute: a potential candidate for phytoremediation of metals—a review. Plants 9, 258. https://doi.org/10.3390/PLANTS9020258.

Salvador Cesa, F., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129. https://doi.org/10.1016/J.SCITOTENV.2017.04.172.

Santos, A.S., Ferreira, P.J.T., Maloney, T., 2021. Bio-based materials for nonwovens. Cellulose 28, 8939–8969. https://doi.org/10.1007/S10570-021-04125-W.

Sarsby, R.W., 2007. Use of 'Limited life geotextiles' (LLGs) for basal reinforcement of embankments built on soft clay. Geotext. Geomembr. 25, 302–310. https://doi.org/10.1016/j.geotexmem.2007.02.010.

Shang, L., Wan, L., Zhou, X., Li, S., Li, X., 2020. Effects of organic fertilizer on soil nutrient status, enzyme activity, and bacterial community diversity in Leymus chinensis steppe in Inner Mongolia, China. PLoS One 15. https://doi.org/10.1371/JOURNAL.PONE.0240559.

Shao et al., n.d.Shao, R.X., Xin, L.F., Zheng, H.F., Li, L.L., Ran, W.L., Mao, J., Yang, Q.H., n.d. Changes in chloroplast ultrastructure in leaves of drought-stressed maize inbred lines. doi:10.1007/s11099-015-0158-6.

Sharma, S.C., Sahoo, A., Chand, R., 2019. Potential use of waste wool in agriculture: an overview. Indian J. Small Ruminants 25, 1. https://doi.org/10.5958/0973-9718.2019.00019.9.

Sharma, S., Kaur, S., Parkash Choudhary, O., Singh, M., Al-Huqail, A.A., Ali, H.M., Kumar, R., Siddiqui, M.H., 2022. Tillage, green manure and residue retention improves aggregate-associated phosphorus fractions under rice–wheat cropping. Sci. Reports 121 (12), 1–13. https://doi.org/10.1038/s41598-022-11106-x.

Shcherbak, I., Millar, N., Robertson, G.P., 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N 2O) emissions to fertilizer nitrogen. Proc. Natl. Acad. Sci. U. S. A. 111, 9199–9204. https://doi.org/10.1073/PNAS.1322434111.

Singh Jadaun, J., Bansal, S., Sonthalia, A., Rai, A.K., Singh, S.P., 2022. Biodegradation of plastics for sustainable environment. Bioresour. Technol. 347, 126697. https://doi.org/10.1016/J.BIORTECH.2022.126697.

Singh, N., Agarwal, S., Jain, A., Khan, S., 2021. 3-dimensional cross linked hydrophilic polymeric network "hydrogels": an agriculture boom. Agric. Water Manag. 253, 106939. https://doi.org/10.1016/J.AGWAT.2021.106939.

Śpitalniak, M., Bogacz, A., Zięba, Z., 2021. The assessment of water retention efficiency of different soil amendments in comparison to water absorbing geocomposite. Mater. 14, 6658. https://doi.org/10.3390/MA14216658.

Steele, C., Reyes, J., Elias, E., Aney, S., Rango, A., 2018. Cascading impacts of climate change on southwestern US cropland agriculture. Clim. Chang. 148, 437–450. https://doi.org/10.1007/S10584-018-2220-4/FIGURES/3.

Subaida, E.A., Chandrakaran, S., Sankar, N., 2009. Laboratory performance of unpaved roads reinforced with woven coir geotextiles. Geotext. Geomembr. 27, 204–210. https://doi.org/10.1016/j.geotexmem.2008.11.009.

Sun, H., Qian, Q., Wu, K., Luo, J., Wang, S., Zhang, C., Ma, Y., Liu, Q., Huang, X., Yuan, Q., Han, R., Zhao, M., Dong, G., Guo, L., Zhu, X., Gou, Z., Wang, W., Wu, Y., Lin, H., Fu, X., 2014. Heterotrimeric G proteins regulate nitrogen-use efficiency in rice. Nat. Genet. 466 (46), 652–656. https://doi.org/10.1038/ng.2958.

Sun, Y., Liu, L., Sun, S., Han, W., Irfan, M., Zhang, X., Zhang, L., Chen, L., 2021. AnDHN, a dehydrin protein from Ammopiptanthus nanus, mitigates the negative effects of drought stress in plants. Front. Plant Sci., 3067 https://doi.org/10.3389/FPLS.2021.788938.

Sun, X., Zhu, B.K., Zhang, S., Zeng, H., Li, K., Wang, B., Dong, Z.F., Zhou, C.C., 2022. New indices system for quantifying the nexus between economic-social development, natural resources consumption, and environmental pollution in China during 1978–2018. Sci. Total Environ. 804, 150180. https://doi.org/10.1016/J.SCITOTENV.2021.150180.

Szerement, J., Szatanik-Kloc, A., Jarosz, R., Bajda, T., Mierzwa-Hersztek, M., 2021. Contemporary applications of natural and synthetic zeolites from fly ash in agriculture and environmental protection. J. Clean. Prod. 311, 127461. https://doi.org/10.1016/J.JCLEPRO.2021.127461.

Szogi, A.A., Shumaker, P.D., Billman, E.D., Bauer, Philip J., Szogi, A.A., Shumaker, P.D., Billman, E.D., Bauer, P.J., 2021. Leaching Potential of Phosphite Fertilizer in Sandy Soils of the Southern Coastal Plain, USA. Environ 8, 126. https://doi.org/10.3390/ENVIRONMENTS8110126.

Tao, J., Zhang, W., Liang, L., Lei, Z., 2018. Effects of eco-friendly carbohydrate-based superabsorbent polymers on seed germination and seedling growth of maize. R. Soc. Open Sci. 5. https://doi.org/10.1098/RSOS.171184.

Team, R.C., 2020. R Core Team (2020). — European Environment Agency [WWW Document]. https://www.eea.europa.eu/data-and-maps/indicators/oxygen-consuming-substances-in-rivers/r-development-core-team-2006 (accessed 5.28.22).

Timonen, K., Sinkko, T., Luostarinen, S., Tampio, E., Joensuu, K., 2019. LCA of anaerobic digestion: emission allocation for energy and digestate. J. Clean. Prod. 235, 1567–1579. https://doi.org/10.1016/J.JCLEPRO.2019.06.085.

Usowicz, B., Lipiec, J., 2022. Assessment of the spatial distribution of cereal yields on sandy soil related to the application of soil-improving cropping systems (SICS). Sci. Total Environ. 830, 154791. https://doi.org/10.1016/J.SCITOTENV.2022.154791.

Varela, S.A., Weigandt, M.N., Willems, P., Bianchi, E., Diez, J.P., Gyenge, J.E., 2016. Physiological status of conifer seedlings treated with radiation, drought and frost stress mitigation techniques: a laboratory assessment. New For. 47, 87–103. https://doi.org/10.1007/s11056-015-9485-5.

Vecchioli, G.I., Del Panno, M.T., Painceira, M.T., 1990. Use of selected autochthonous soil bacteria to enhanced degradation of hydrocarbons in soil. Environ. Pollut. 67, 249–258. https://doi.org/10.1016/0269-7491(90)90190-N.

Venkateswarlu, H., Ujjawal, K.N., Hegde, A., 2018. Laboratory and numerical investigation of machine foundations reinforced with geogrids and geocells. Geotext. Geomembr. 46, 882–896. https://doi.org/10.1016/j.geotexmem.2018.08.006.

Walling, E., Vaneeckhaute, C., 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: a review of emission factors and their variability. J. Environ. Manag. 276, 111211. https://doi.org/10.1016/J.JENVMAN.2020.111211.

Wan, Y., Wu, C., Xue, Q., Hui, X., 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci. Total Environ. 654, 576–582. https://doi.org/10.1016/J.SCITOTENV.2018.11.123.

Wei, Y., Durian, D.J., 2014. Rain water transport and storage in a model sandy soil with hydrogel particle additives. Eur. Phys. J. E 3710 (37), 1–11. https://doi.org/10.1140/EPJE/I2014-14097-X.

Wiewel, B.V., Lamoree, M., 2016. Geotextile composition, application and ecotoxicology—A review. J. Hazard. Mater. https://doi.org/10.1016/j.jhazmat.2016.04.060.

Xiong, B., Loss, R.D., Shields, D., Pawlik, T., Hochreiter, R., Zydney, A.L., Kumar, M., 2018. Polyacrylamide degradation and its implications in environmental systems. npj Clean Water 11 (1), 1–9. https://doi.org/10.1038/s41545-018-0016-8.

Yang, W., Li, P., Guo, S., Song, R., Yu, J., Yang, W., Li, P., Guo, S., Song, R., Yu, J., 2019. Co-application of soil superabsorbent polymer and foliar fulvic acid to increase tolerance to water deficit maize: photosynthesis, water parameters, and proline. Chil. J. Agric. Res. 79, 435–446. https://doi.org/10.4067/S0718-58392019000300435.

Yang, H., Li, Y., Cao, Y., Shi, W., Xie, E., Mu, N., Du, G., Shen, Y., Tang, D., Cheng, Z., 2022. Nitrogen nutrition contributes to plant fertility by affecting meiosis initiation. Nat. Commun. 131 (13), 1–15. https://doi.org/10.1038/s41467-022-28173-3.

Yang, Y., Li, Z., Yan, C., Chadwick, D., Jones, D.L., Liu, E., Liu, Q., Bai, R., He, W., 2022. Kinetics of microplastic generation from different types of mulch films in agricultural soil. Sci. Total Environ. 814, 152572. https://doi.org/10.1016/J.SCITOTENV.2021.152572.

Yin, K., Wang, D., Zhao, H., Wang, Y., Guo, M., Liu, Y., Li, B., Xing, M., 2021. Microplastics pollution and risk assessment in water bodies of two nature reserves in Jilin Province: correlation analysis with the degree of human activity. Sci. Total Environ. 799, 149390. https://doi.org/10.1016/J.SCITOTENV.2021.149390.

Yugandhar, P., Veronica, N., Subrahmanyam, D., Brajendra, P., Nagalakshmi, S., Srivastava, A., Voleti, S.R., Sarla, N., Sundaram, R.M., Sevanthi, A.M., Singh, A.K., Mangrauthia, S.K., 2022. Revealing the effect of seed phosphorus concentration on seedling vigour and growth of rice using mutagenesis approach. Sci. Reports 121 (12), 1–22. https://doi.org/10.1038/s41598-022-04983-9.

Yun, K.K., Hossain, M.S., Han, S., Seunghak, C., 2022. Rheological, mechanical properties, and statistical significance analysis of shotcrete with various natural fibers and mixing ratios. Case Stud. Constr. Mater. 16, e00833. https://doi.org/10.1016/J.CSCM.2021.E00833.

Zaki, H.E.M., Radwan, K.S.A., 2022. Response of potato (Solanum tuberosum L.) cultivars to drought stress under in vitro and field conditions. Chem. Biol. Technol. Agric. 91 (9), 1–19. https://doi.org/10.1186/S40538-021-00266-Z 2021.

Zang, H., Zhou, J., Marshall, M.R., Chadwick, D.R., Wen, Y., Jones, D.L., 2020. Microplastics in the agroecosystem: are they an emerging threat to the plant-soil system? Soil Biol. Biochem. 148, 107926. https://doi.org/10.1016/J.SOILBIO.2020.107926.

Zhang, N., Zhao, B., Zhang, H.J., Weeda, S., Yang, C., Yang, Z.C., Ren, S., Guo, Y.D., 2013. Melatonin promotes water-stress tolerance, lateral root formation, and seed germination in cucumber (Cucumis sativus L.). J. Pineal Res. 54, 15–23. https://doi.org/10.1111/J.1600-079X.2012.01015.X.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nat. 5287580 (528), 51–59. https://doi.org/10.1038/nature15743.

Zhang, Y., Lei, H., Zhao, W., Shen, Y., Xiao, D., 2018. Comparison of the water budget for the typical cropland and pear orchard ecosystems in the North China plain. Agric. Water Manag. 198, 53–64. https://doi.org/10.1016/J.AGWAT.2017.12.027.

Zhang, J., Soltani, A., Deng, A., Jaksa, M., 2019. Mechanical performance of jute fiber-reinforced micaceous clay composites treated with ground-granulated blast-furnace slag. Materials (Basel). 12, 576. https://doi.org/10.3390/ma12040576.

Zhang, K., Feng, W., Jin, C., 2020. Protocol efficiently measuring the swelling rate of hydrogels. MethodsX 7, 100779. https://doi.org/10.1016/J.MEX.2019.100779.

Zhang, W., Wang, P., Liu, S., Chen, J., Chen, R., He, X., Ma, G., Lei, Z., 2021. Factors affecting the properties of superabsorbent polymer hydrogels and methods to improve their performance: a review. J. Mater. Sci. 56, 16223–16242. https://doi.org/10.1007/S10853-021-06306-1/TABLES/7.

Zhang, S., Fan, J., Zhang, F., Wang, H., Yang, L., Sun, X., Cheng, M., Cheng, H., Li, Z., 2022. Optimizing irrigation amount and potassium rate to simultaneously improve tuber yield, water productivity and plant potassium accumulation of drip-fertigated potato in Northwest China. Agric. Water Manag. 264, 107493. https://doi.org/10.1016/J.AGWAT.2022.107493.

Zhao, X., Liu, L., Wang, Y., Dai, H., Wang, D., Cai, H., 2008. Influences of partially hydrolyzed polyacrylamide (HPAM) residue on the flocculation behavior of oily wastewater produced from polymer flooding. Sep. Purif. Technol. 62, 199–204. https://doi.org/10.1016/J.SEPPUR.2008.01.019.

Zhou, D., Chen, J., Wu, J., Yang, J., Wang, H., 2021. Biodegradation and catalytic-chemical degradation strategies to mitigate microplastic pollution. Sustain. Mater. Technol. 28, e00251. https://doi.org/10.1016/J.SUSMAT.2021.E00251.