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Trwałość biodegradowalnych geokompozytów sorbujących wodę

The durability of biodegradable water absorbing geocomposites

Rozprawa doktorska

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Spis treści

CYKL PUBLIKACJI WCHODZĄCYCH W SKŁAD ROZPRAWY DOKTORSKIEJ 4

STRESZCZENIE 5

1. WSTĘP 8

   1.1. Znaczenie dodatków doglebowych 8

   1.2. Zanieczyszczenie środowiska geosyntetykami 9

   1.3. Potencjał materiałów biodegradowalnych 11

   1.4. Opracowanie innowacyjnego dodatku doglebowego 12

2. HIPOTEZY BADAWCZE I CEL PRACY 14

3. ORGANIZACJA BADAŃ 15

   3.1. Doświadczenie polowe 15

   3.2. Materiały 17

   3.2.1. Produkcja prototypów 19

   3.3. Metody badawcze 19

   3.3.1. Materiał roślinny 19

   3.3.2. Materiał włókienniczy 20

   3.3.3. Właściwości gleby 20

   3.3.5. Analiza statystyczna 21

   3.4. Etapy badań 22

4. OMÓWIENIE I DYSKUSJA WYNIKÓW 23

   4.1. Przegląd właściwości włókien biodegradowalnych 23

   4.2. Biodegradacja elementów BioWAG w warunkach rzeczywistych 24

   4.3. Określenie wpływu BioWAG na wegetację wybranych gatunków traw 28

5. PODSUMOWANIE I WNIOSKI 33

BIBLIOGRAFIA 35

DOROBEK NAUKOWY 45

ZAŁĄCZNIKI 50

   Publikacja 1 51

   Publikacja 2 72

   Publikacja 3 89

   Publikacja 4 109

CYKL PUBLIKACJI WCHODZĄCYCH W SKŁAD ROZPRAWY DOKTORSKIEJ

Lp.	Publikacja	Punkty MNiSW	IF	Udział %
P1	**Marczak D.**, Lejcuś K., Misiewicz J. 2020. *Characteristics of biodegradable textiles used in environmental engineering: a comprehensive review*. Journal of Cleaner Production. 268, 122129. DOI:10.1016/j.jclepro.2020.122129	140	9,297	65
P2	**Marczak D.**, Lejcuś K., Grzybowska-Pietras J., Biniaś W., Lejcuś I., Misiewicz J. 2020. *Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation*. Sustainable Materials and Technologies. 26, e00235. DOI:10.1016/j.susmat.2020.e00235	200	7,053	60
P3	**Marczak D.**, Lejcuś, K., Kulczycki, G., Misiewicz, J. 2022. *Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility*. Science of the Total Environment. 844, 157169. DOI:10.1016/j.scitotenv.2022.157169	200	9,800	70
P4	**Marczak D.**, Lejcuś K., Lejcuś I., Misiewicz J. 2023. Sustainable Innovation: Turning Waste into Soil Additives. Materials. 16, 2900. DOI:10.3390/ma16072900	140	3,400	70

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STRESZCZENIE

W ostatnich latach problemy dotyczące niedoboru wody, utraty żyzności gleb oraz zanieczyszczenia środowiska przybierają na znaczeniu. Zjawiska te mają szereg negatywnych skutków widocznych nie tylko w rolnictwie, ale także w inżynierii środowiska, gdzie wybrane gatunki roślin stanowią element ubezpieczenia biotechnicznego budowli ziemnych. Jedną z metod przeciwdziałania tym negatywnym zjawiskom i adaptacji do zmian klimatu, jest rozwój nowych technologii zgodnych z założeniami zrównoważonego rozwoju. Mając na uwadze zidentyfikowane problemy oraz obecne trendy zbadano właściwości oraz sprawdzono skuteczność innowacyjnej technologii w postaci biodegradowalnego geokompozytu sorbującego wodę (BioWAG). BioWAG przeznaczone są do magazynowania wody w glebie, w taki sposób, aby była ona dostępna dla roślin.

W niniejszej rozprawie doktorskiej założono następujące cele: (1) analiza biodegradowalności w warunkach rzeczywistych wybranych materiałów stanowiących element BioWAG oraz (2) ocena możliwości wykorzystania BioWAG do wspomagania wegetacji wybranych gatunków traw. W ramach przeprowadzonych badań terenowych oraz laboratoryjnych wyznaczono właściwości fizyko-chemiczne wybranych elementów BioWAG, scharakteryzowano materiał roślinny oraz wyznaczono wybrane parametry gleby.

Uzyskane wyniki pozwoliły na potwierdzenie postawionej hipotezy badawczej udowadniając, że zastosowanie materiałów biodegradowalnych w postaci włóknin na bazie naturalnych włókien odpadowych, umożliwia ich stopniową biodegradację w glebie przy jednoczesnym wspomaganiu wegetacji wybranych gatunków traw. Na podstawie przeprowadzonych badań wykazano, że włókna odpadowe, takie jak wełna, juta i len odznaczają się odpowiednimi właściwościami fizyko-chemicznymi i stanowią atrakcyjny materiał do produkcji BioWAG. Na stanowiskach z BioWAG zaobserwowano wzrost żyzności gleby. BioWAG przez trzy sezony wegetacyjne pozytywnie wpływały na wegetację wybranych gatunków traw, zwiększając przyrosty nadziemnych części o nawet 430% oraz systemu korzeniowego o nawet 220% w porównaniu do stanowisk kontrolnych.

Przedstawione wyniki dają podstawę do wdrożenia rozwiązania, które pozwala zredukować dawkę nawodnień oraz nawozów niezbędnych do prawidłowego rozwoju wybranych gatunków traw, przy jednoczesnym uwzględnieniu założeń gospodarki cyrkulacyjnej oraz zasad zrównoważonego rozwoju.

Słowa kluczowe: biodegradowalny geokompozyt sorbujący wodę, włókna naturalne, zrównoważone technologie, wspomaganie wegetacji, adaptacja do zmian klimatu, gospodarka cyrkulacyjna

ABSTRACT

The issues concerning water scarcity, soil fertility decline and environmental pollution have received increasing attention in recent years. These phenomena involve many negative effects in agriculture and environmental engineering, where selected plant species serve as biotechnical insurance for earth structures. Developing new technologies in line with sustainable development is one of the methods to tackle these adverse effects and adapt to climate change. Given the specific problems that have been identified and current trends, the properties and effectiveness of an innovative technology in the form of a biodegradable water-absorbing geocomposite (BioWAG) were explored. BioWAGs are developed to store water in the soil to make it available to plants.

The aims of this doctoral dissertation were as follows: (1) to analyse the biodegradability in real-life conditions of selected BioWAG element materials and (2) to assess the potential of using BioWAG to support vegetation of selected grass species. In the course of field and laboratory tests, the physico-chemical properties of selected BioWAG elements were identified, plant material was also characterised, and selected soil parameters were determined.

The findings confirm the research hypothesis, proving that the use of biodegradable materials in the form of natural fibre-based nonwoven waste materials enables their gradual biodegradation in the soil with the simultaneous promotion of the vegetation of selected grass species. The research shows that waste fibres such as wool, jute and linen are characterised by suitable physical and chemical properties and represent an attractive material for the production of BioWAG. An increased soil fertility was noticed on the BioWAG sites. BioWAG had a positive impact on the vegetation of selected grass species for three growing seasons, boosting aboveground growth by up to 430% and the root system by up to 220% when compared to control sites.

The findings presented serve as a good reason to implement a solution that reduces the amount of irrigation and fertiliser necessary for the proper development of the selected grass species, while also considering the concept of circular economy and sustainability.

Keywords: biodegradable water absorbing geocomposite, natural fibres, sustainable technologies, vegetation support, climate change adaptation, circular economy

Skróty i akronimy

BioWAG	biodegradowalny geokompozyt sorbujący wodę
PBS	poli(bursztynian butylenu)
PCL	polikaprolakton
PET	poli(tereftalan etylenu)
PHA	polihydroksyalkanian
PHB	polihydroksymaślan
PLA	polilaktyd, poli(kwas mlekowy)
PP	polipropylen
RWC	względna zawartość wody
SAP	superabsorbent polimerowy
WAG	geokompozyt sorbujący wodę

1. WSTĘP

1.1. Znaczenie dodatków doglebowych

Obecnie obserwowane zmiany klimatu, charakteryzujące się nieregularnymi opadami atmosferycznymi i wyższymi średnimi temperaturami powietrza, stanowią poważne zagrożenie dla ekosystemów, zdrowia ludzi i stabilności gospodarki (Baghbanzadeh i in. 2017). W ostatnich dziesięcioleciach częstotliwość i zasięg oddziaływania suszy znacząco wzrosły. Prognozuje się, że w perspektywie kolejnych lat sytuacja będzie ulegała dynamicznemu pogorszeniu, a ograniczony dostęp do wody może dotknąć blisko dwa miliardy ludzi (Roa i in. 2021). Problem niedoborów wody jest szczególnie zauważalny na obszarach z glebami przepuszczalnymi, o niskiej zdolności do retencjonowania wody oraz zatrzymywania składników odżywczych. W związku z powyższym, koniecznym jest poszukiwanie oraz wdrażanie innowacyjnych rozwiązań łagodzących skutki susz z uwzględnieniem racjonalnego gospodarowania wodami opadowymi w środowisku (Jatav i in. 2021; Li i in. 2022; Anagnostopoulou i in. 2022).

Jednym ze sprawdzonych sposobów adaptacji do zmian klimatu jest stosowanie dodatków doglebowych, wpływających pozytywnie na retencję i strukturę gleby (Wiewel, Lamoree 2016; Sülar, Devrim 2019). Popularnymi dodatkami w tym zakresie są m.in.: zeolity, attapulgity, bentonity i superabsorbenty polimerowe (SAP) (Nakhli i in. 2017; Jahan, Nassiri Mahallati 2020; Karami i in. 2020; Zhang i in. 2006; Elbarbary i in. 2017; Śpitalniak i in. 2019). Zeolity to krystaliczne glinokrzemiany, które składają się z systemu połączonych komór i kanałów, dzięki czemu charakteryzują się dużą pojemnością sorpcyjną (Szerement i in. 2021; Gatta, Lotti 2019). Bentonity są skałami ilastymi, które dzięki swojej strukturze i możliwości pęcznienia poprawiają zdolności retencyjne gleby (Manjaiah i in. 2019; Mi i in. 2017). Do najatrakcyjniejszych materiałów zwiększających zdolności retencyjne podłoża należą aktualnie superabsorbenty polimerowe, znane również jako hydrożele (Śpitalniak, Bogacz, Zięba 2021; Zhang i in. 2021; Pereira i in. 2012). SAPy charakteryzują się zdolnością do pochłaniania bardzo dużych ilości wody, a 1 g ich suchej postaci może pochłonąć około 300-400 g wody (Lejcuś i in. 2015). Podstawowym zadaniem SAP jest pochłonięcie, przechowanie oraz dostarczenie wody roślinie w momencie zapotrzebowania. W konsekwencji hydrożele poprawiają efektywność wykorzystania wody i składników odżywczych poprzez ograniczenie parowania, infiltracji i wypłukiwania składników odżywczych w głąb profilu glebowego (Miljković, Gajić, Nikolić 2021; Arican i in. 2021; Lejcuś i in. 2015). W warunkach rzeczywistych hydrożele są najczęściej aplikowane przez bezpośrednie wymieszanie ich z glebą. Ograniczona przestrzeń porowa oraz obciążenie warstwą gleby, negatywnie wpływają na właściwości superabsorbentów polimerowych. Badania dotyczące zdolności sorpcyjnych SAP pod obciążeniem wskazują, że już kilkucentymetrowa warstwa gleby może znacząco obniżyć ich zdolność do magazynowania wody (Misiewicz i in. 2019). Z uwagi na powyższe, działanie hydrożeli przy tradycyjnym sposobie ich aplikacji jest znacząco ograniczone.

W ostatnich latach obserwuje się dynamiczny rozwój dodatków doglebowych w postaci geotekstyliów, w tym geowłóknin (Wiewel, Lamoree 2016; Sülar, Devrim 2019). Szacuje się, że każdego roku zużywanych jest blisko 1500 milionów metrów kwadratowych tego typu materiałów (Prambauer i in. 2019; Marczak, Lejcuś, Misiewicz 2020). Tak duże zainteresowanie wynika z licznych korzyści stosowania tych materiałów oraz szerokiego wachlarza ich zastosowań, m.in. w inżynierii środowiska, rolnictwie, ogrodnictwie i budownictwie (Venkateswarlu, Ujjawal, Hegde 2018; Subaida, Chandrakaran, Sankar 2009). Włókniny mogą pełnić szereg funkcji, w tym: hydrauliczne (drenaż, filtracja), mechaniczne (wzmocnienie, zbrojenie, zabezpieczenie przeciwerozyjne, separacja) i biologiczne (ochrona, rekultywacja) (Onuaguluchi, Banthia 2016; Hsieh i in. 2017; Marczak i in. 2020; Methacanon i in. 2010). Od niedawna włókniny są również stosowane w rolnictwie i ogrodnictwie, jako substytut nawozów i materiałów poprawiających retencję (Broda 2019; Marczak i in. 2020).

W inżynierii środowiska geowłókniny są z powodzeniem stosowane, jako materiały przeciwerozyjne. Skarpy obiektów ziemnych bezpośrednio po zakończeniu budowy lub modernizacji, pozbawione okrywy roślinnej, są erodowane przez wiatr i opady atmosferyczne (Subaida, Chandrakaran, Sankar 2009; Sarsby 2007; Venkateswarlu, Ujjawal, Hegde 2018; Cao i in. 2020). Sprawdzonym i z powodzeniem stosowanym rozwiązaniem, utrwalającym zewnętrzne elementy budowli ziemnych, jest trwała pokrywa roślinna. Rośliny korzeniąc się w warstwie narażonej na erozję tworzą połączenie o dużej wytrzymałości. Poważnym wyzwaniem jest zapewnienie tej roślinności odpowiednich warunków do wegetacji (Broda i in. 2018; Lejcuś i in. 2015). Obiekty ziemne charakteryzują się występowaniem gleb o niskich zdolnościach retencyjnych i żyzności, gdzie składniki odżywcze są łatwo wymywane przez wodę opadową lub stają się niedostępne dla roślin w okresach suszy (Medyńska-Juraszek i in. 2021; Stefaniuk i in. 2018). Zwiększenie retencji glebowej, żyzności gleb oraz rekultywacja terenów trudnych siedliskowo stały się jednymi z głównych wyzwań skutecznego wprowadzania ubezpieczeń biotechnicznych na obiekty inżynierskie (León i in. 2017; Solazzo i in. 2013; Moura i in. 2016).

1.2. Zanieczyszczenie środowiska geosyntetykami

Obecnie większość geowłóknin, stosowanych w aplikacjach środowiskowych, jest wytwarzana z polipropylenu (PP) oraz poli(tereftalanu etylenu) (PET), które nie ulegają biodegradacji i stanowią obciążenie dla środowiska (Szostak-Kotowa 2004; Hejazi i in. 2012). Szacuje się, że przemysł tekstylny Unii Europejskiej, w tym produkcja geosyntetyków, jest odpowiedzialny za wytwarzanie około 16 milionów ton odpadów rocznie. Wiele z tych odpadów trafia na składowiska, jest spalanych lub co gorsza w niekontrolowany sposób trafia do gleby i wód powierzchniowych (Nguyen, Grzybowska-Pietras, Broda 2021). Ponadto, sektor ten produkuje corocznie znaczące ilości innych zanieczyszczeń - w 2015 r. wygenerował blisko 2 miliardy ton CO_2 i pochłonął około 100 miliardów metrów sześciennych wody, co stanowi obciążenie zagrażające zdrowiu i życiu ludzi (Palacios-Mateo, van der Meer, Seide 2021; Stone i in. 2020; Sandin, Peters 2018).

Dostępne w literaturze badania koncentrują się głównie na zanieczyszczeniu wód powierzchniowych tworzywami sztucznymi (Monkul, Özhan 2021; Möller, Löder, Laforsch 2020). Tymczasem każdego roku pogłębia się globalny problem zanieczyszczenia gleb (Boregowda i in. 2022; Boots, Russell, Green 2019). Szacuje się, że akumulacja tworzyw sztucznych w glebie jest ponad 20 razy większa, niż w przypadku akwenów wodnych (Sobhani i in. 2022; Okeke i in. 2022). Zanieczyszczenia mogą przedostawać się do gleb bezpośrednio podczas prowadzenia nawodnień np. z osadami ściekowymi lub pośrednio w wyniku stopniowej degradacji materiałów syntetycznych (Bandini i in. 2022; Corradini i in. 2019). Tworzywa sztuczne obecne w glebie mogą powodować szereg negatywnych zjawisk, m.in. poprzez intensyfikowanie koncentracji metali ciężkich, związków organicznych i innych toksycznych substancji (Sarasini, Fiore 2018; Street, Bernasconi 2021). Co więcej, mogą negatywnie wpłynąć na aktywność mikroorganizmów glebowych (Zhou i in. 2021; Wan i in. 2019; Guo i in. 2020; Zang i in. 2020; Marczak i in. 2022).

Obecnie za jedno z głównych źródeł zanieczyszczeń gleb uważa się włókna syntetyczne, które są wprowadzane do środowiska m.in. w postaci agrowłóknin, geowłóknin, geotkanin, geosiatek, geomat oraz geokompozytów (Kamble, Behera 2021; Dierickx, Van Den Berghe 2004). Inżynieria środowiska, budownictwo, rolnictwo i ogrodnictwo są głównymi odbiorcami wymienionych powyżej materiałów, przez co w znacznym stopniu przyczyniają się do zanieczyszczenia środowiska. Szacuje się, że blisko 50% wyrobów z tworzyw sztucznych stosowanych w aplikacjach środowiskowych jest użytkowanych krócej niż 30 dni, a w przypadku materiałów stosowanych w rolnictwie i inżynierii środowiska czas eksploatacji często ogranicza się do jednego sezonu wegetacyjnego (Hahladakis i in. 2018; Marczak i in. 2020). Z uwagi na powyższe, produkcja materiałów biodegradowalnych, przyjaznych dla środowiska powinna być uznawana za priorytetowy kierunek działalności naukowej i przemysłowej (Saberi Riseh i in. 2023). W aplikacjach środowiskowych powinny być wdrażane alternatywne rozwiązania, zgodne z założeniami zrównoważonego rozwoju oraz gospodarki cyrkulacyjnej. W tym przypadku nadrzędnym celem jest ponowne wykorzystanie materiałów odpadowych stanowiących np. produkt uboczny przemysłu tekstylnego, hodowli zwierząt, czy uprawy roślin (Onuaguluchi, Banthia 2016; Sanjay i in. 2018).

1.3. Potencjał materiałów biodegradowalnych

Jednym ze sposobów ograniczenia zużycia zasobów nieodnawialnych i zanieczyszczenia środowiska jest poszukiwanie naturalnych odpowiedników tworzyw petrochemicznych, które będą wykazywały odpowiednie właściwości fizyczne i chemiczne (Chauhan, Mittal, Mohanty 2008; Andrady 2017). W ostatnich latach na popularności zyskują materiały produkowane z polimerów biodegradowalnych (Yates, Barlow 2013). Niestety, proces ich produkcji jest nadal stosunkowo drogi, co znacząco utrudnia ich powszechne stosowanie, szczególnie w kontekście aplikacji środowiskowych.

Drugą grupę materiałów biodegradowalnych stanowią włókna naturalne, pozyskiwane z surowców pochodzenia roślinnego lub zwierzęcego (Melelli i in. 2022; McNeil, Sunderland, Zaitseva 2007; Pegoretti i in. 2014; Zhao i in. 2022). Wśród najbardziej atrakcyjnych pod względem aplikacyjnym, można wyróżnić m.in. jutę, len, włókno kokosowe, słomę, konopie, bambus i wełnę (Rawal, M.M.A. Sayeed 2013; Shanks, Hodzic, Ridderhof 2006; Lekha 2004; Sukudom i in. 2019; Sarsby 2007; Kumar, Das 2018; Yang i in. 2016). Włókna roślinne charakteryzują się pożądanymi w aplikacjach środowiskowych właściwościami fizycznymi i chemicznymi (Rawal, M. M.A. Sayeed 2013; Sumi, Unnikrishnan, Mathew 2018). Ich głównym składnikiem jest celuloza, która zapewnia odpowiednią wytrzymałość mechaniczną. Wykazują one również wysoką wodochłonność, dzięki czemu ich zastosowanie prowadzi m.in. do ograniczenia spływu powierzchniowego, podczas opadów atmosferycznych oraz stopniowe uwalnianie wilgoci do gleby w okresach niedoboru wody (Gowthaman, Nakashima, Kawasaki 2018; Bordoloi, Garg, Sekharan 2017). Włókna zwierzęce, w tym wełna owcza odznaczają się wysoką wytrzymałością, dobrymi właściwości termicznymi i higroskopijnymi (Corscadden, Biggs, Stiles 2014; Galán-Marín, Rivera-Gómez, Petric-Gray 2010; Marczak, Lejcuś, Misiewicz 2020). A co najważniejsze, biodegradacja materiałów pochodzenia zwierzęcego prowadzi do powstawania łatwo przyswajalnych dla roślin form azotu, fosforu i siarki, które stanowią naturalny nawóz dla roślin (Broda 2019). Mimo powszechnego dostępu do włókien naturalnych, ich potencjał w formie włókniny nadal nie jest doceniany. Wynika to przede wszystkim z ograniczonej wytrzymałości oraz żywotności tych materiałów. Kluczem do skutecznego stosowania biodegradowalnych geowłóknin jest określenie ich funkcji, wymaganych właściwości oraz oszacowanie czasu ich eksploatacji, a następnie odpowiednie dobranie surowca (Ku i in. 2011; Sgriccia, Hawley, Misra 2008). Koncepcja wprowadzania materiałów naturalnych, o określonym czasie degradacji wiąże się przede wszystkim ze zdefiniowaniem czasu, w którym dany materiał powinien spełnić powierzone mu zadania. Materiały używane do produkcji biodegradowalnych włóknin powinny być dobrane tak, aby stopniowa utrata ich właściwości była proporcjonalna do poprawy warunków gruntowych (Mwasha 2009). Geowłókniny z naturalnych materiałów zainstalowane w glebie zapewniają natychmiastową ochronę, a poprzez postępującą biodegradację, dostarczają materii organicznej i składników odżywczych, pozytywnie wpływając na wegetację roślin (Broda i in. 2016).

Powszechnie dostępne włókna naturalne to często niskiej jakości materiał odpadowy (Bousshine i in. 2022; Fang, Meng, Zhang 2022; Al Faruque i in. 2021). Zastosowanie naturalnych włókien odpadowych, przy uwzględnieniu ekonomicznych metod ich przetwarzania, może stworzyć realną szansę ograniczenia zastosowania syntetycznych dodatków doglebowych. Alternatywne metody zagospodarowania naturalnych włókien odpadowych są obecnie pożądane ze względu na nasilający się problem ich racjonalnego wykorzystania. Obserwowany jest dynamiczny wzrost akumulacji naturalnych włókien, które stanowią odpad pochodzący z hodowli owiec, uprawy roślin włóknistych oraz przemysłu tekstylnego (Yousef i in. 2019; Dissanayake i in. 2018; Nematian, Keske, Ng'ombe 2021). Wełna pochodząca z hodowli owiec mięsnych lub mlecznych stanowi materiał niskiej jakości, który według przepisów Komisji Europejskiej zaliczany jest do materiałów odpadowych kategorii trzeciej (Bhavsar i in. 2021). Ze względu na niską jakość tego surowca znajduje on dość wąskie spektrum zastosowań w przemyśle tekstylnym i jest postrzegany jako trudny do zagospodarowania odpad (Petek, Marinšek Logar 2021). W związku z tym, warto poszukiwać i rozpowszechniać nowe trendy, które opierają się na zasadach gospodarki cyrkulacyjnej, w myśl której odpady włókiennicze, nie trafiają na składowiska odpadów, lecz są ponownie wykorzystywane w innych zastosowaniach, np. środowiskowych (Shirvanimoghaddam i in. 2020; Tobin, Urban-Rich 2022).

1.4. Opracowanie innowacyjnego dodatku doglebowego

Biorąc pod uwagę wskazane wyżej problemy środowiskowe, opracowano nowy typ dodatku doglebowego, nazwanego geokompozytem absorbującym wodę (WAG). Jego przestrzenna konstrukcja pozwala w pełni wykorzystać zdolności sorpcyjne SAP i wyeliminować ich wcześniej opisane ograniczenia. W podstawowej wersji WAG składa się z trzech elementów: włókniny, szkieletu wewnętrznego oraz SAP. Włóknina, o odpowiednich właściwościach hydraulicznych, przechwytuje wodę z otoczenia i transportuje ją do wnętrza WAG, gdzie jest magazynowana przez SAP. Szkielet wykonany z przestrzennej siatki, ma za zadanie zabezpieczyć konstrukcję przed wpływem obciążenia (gleby) oraz stworzyć wolną przestrzeń wymaganą do swobodnego pęcznienia SAP (Marczak i in. 2020; Oksińska i in. 2016; Lejcuś, Śpitalniak, Dąbrowska 2018; Lejcuś i in. 2016).

WAG magazynuje wodę w glebie w taki sposób, aby była ona dostępna dla roślin (Lejcuś i in. 2015; Bąbelewski, Pancerz, Dębicz 2017). System korzeniowy roślin, w wyniku zjawiska hydrotropizmu, orientuje się, gdzie jest wyższe nasycenie wodą. W efekcie system korzeniowy intensywnie rozwija się w kierunku źródła wody, w tym przypadku w kierunku WAG. Korzenie roślin mogą swobodnie przerastać przez włókninę do wnętrza WAG i wykorzystując siłę ssącą mogą pobrać nawet 95% zgromadzonej w nim wody. Proces pochłaniania i oddawania wody przez WAG może zachodzić wielokrotnie. W zależności od przeznaczenia, geokompozyt sorbujący wodę może mieć różne kształty i rozmiary, jednak zazwyczaj jest aplikowany w postaci przestrzennej maty (Śpitalniak, Bogacz, Zięba 2021; Lejcuś i in. 2015).

WAG mogą być z powodzeniem stosowane w aplikacjach środowiskowych m.in.:

- na wałach przeciwpowodziowych oraz nasypach drogowych, gdzie wspomagają prawidłowy rozwój roślinności, stanowiącej element ubezpieczenia biotechnicznego,
- na terenach zdegradowanych i trudnych siedliskowo, np. do rekultywacji składowisk odpadów,
- w przestrzeni zurbanizowanej, gdzie wspomagają prawidłowy rozwój zieleni miejskiej, na zielonych dachach i ścianach,
- w wybranych gałęziach rolnictwa i ogrodnictwa, np. w uprawie bylin lub roślin jagodowych.

Dotychczas WAG były produkowane wyłącznie w wersji syntetycznej, która została opracowana w ramach projektu nr POIG.01.03.01-00-181/09-00, pt. *GEOSAP – Geokompozyty sorbujące wodę – innowacyjne technologie wspomagające wegetację roślin* (Narodowe Centrum Badań i Rozwoju), a następnie opatentowana (PL 211198; EP 2560472) i skomercjalizowana. Problemy dotyczące zanieczyszczenia środowiska tworzywami sztucznymi, duży potencjał materiałów biodegradowalnych oraz zapotrzebowanie rynku, stanowiły istotną motywację do opracowania nowej biodegradowalnej wersji geokompozytów sorbujących wodę (BioWAG). W związku z powyższym w niniejszej rozprawie podjęto się badań nad określeniem właściwości BioWAG. Prace badawcze dotyczące opracowania BioWAG realizowano w ramach projektu nr POIR.04.01.04-00-0061/16, pt. *Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin* (Narodowe Centrum Badań i Rozwoju).

2. HIPOTEZY BADAWCZE I CEL PRACY

Główne założenia prezentowanej rozprawy doktorskiej oparto na następującej hipotezie badawczej:

1. Zastosowanie w BioWAG materiałów biodegradowalnych w postaci włóknin na bazie naturalnych włókien odpadowych, umożliwia ich stopniową biodegradację w glebie przy jednoczesnym wspomaganiu wegetacji wybranych gatunków traw (**H1**).

Głównymi celami przeprowadzonych badań, których wyniki opublikowano w spójnym tematycznie cyklu publikacji, było:

1. Analiza biodegradowalności w warunkach rzeczywistych wybranych materiałów stanowiących element BioWAG.
2. Ocena możliwości wykorzystania BioWAG do wspomagania wegetacji wybranych gatunków traw.

Cele główne pracy realizowano w oparciu o następujące cele szczegółowe:

1. przegląd właściwości biodegradowalnych wyrobów włókienniczych oraz wskazanie najlepszych do zastosowań środowiskowych (**P1**);
2. określenie zmian parametrów fizyko-chemicznych zachodzących we włókninach i pozostałych elementach BioWAG pod wpływem wybranych czynników środowiskowych (**P2; P3**);
3. określenie wpływu BioWAG na wegetację wybranych gatunków traw (**P3; P4**);
4. określenie procesów towarzyszących biodegradacji wybranych elementów BioWAG, m.in. zidentyfikowanie mikro- i makroelementów uwalnianych do gleby oraz efektywnie pobieranych przez wybrane gatunki traw (**P3; P4**).

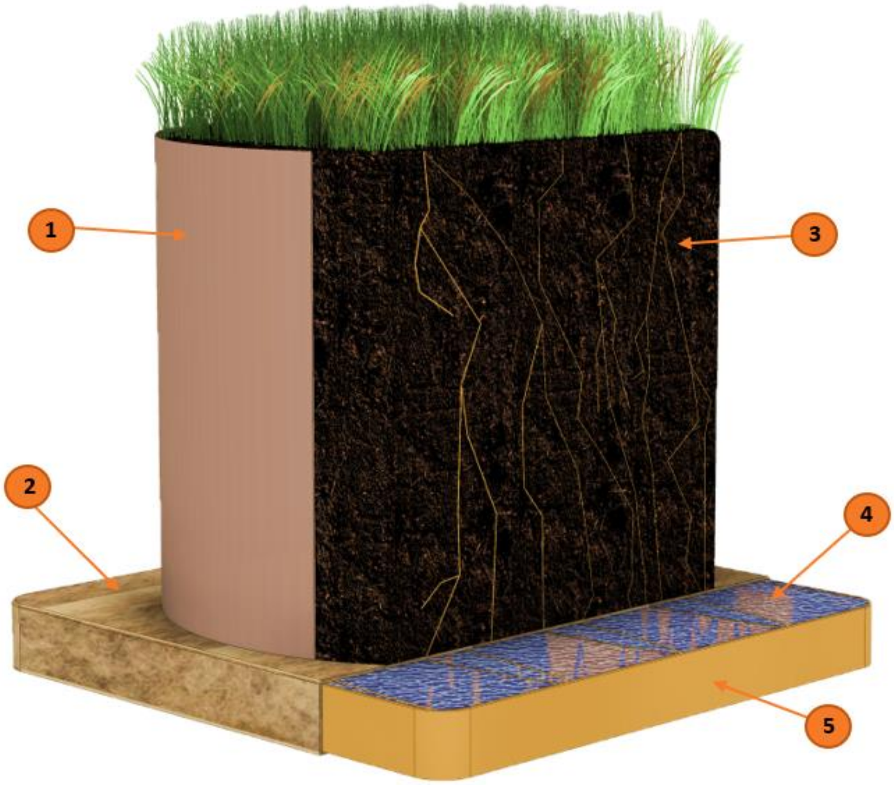
3. ORGANIZACJA BADAŃ

3.1. Doświadczenie polowe

Doświadczenie prowadzono w okresie od maja 2018 do października 2020 roku na poletku doświadczalnym zlokalizowanym na terenie Wydziałowego Obserwatorium Agro- i Hydrometeorologii Wrocław-Swojec, Uniwersytetu Przyrodniczego we Wrocławiu (51°07′N, 17°10′E). Obszar badawczy położony był w południowo-zachodniej części Polski, w strefie klimatu umiarkowanego ciepłego. Średnia suma rocznych opadów atmosferycznych na nizinach Dolnego Śląska wynosi 560-600 mm (Pęczkowski i in. 2018). Dane meteorologiczne z analizowanego okresu badawczego przedstawiono i przeanalizowano w publikacjach **P2**, **P3** i **P4** (*Autorzy wykorzystali dane meteorologiczne z Obserwatorium Agro i Hydrometeorologii Wrocław-Swojec Uniwersytetu Przyrodniczego we Wrocławiu (WOAiHW-S)*).

Poletko doświadczalne podzielono na trzy bloki o jednakowych wymiarach, z wyznaczonymi strefami buforowymi. Każdy z bloków oznaczał jeden z trzech sezonów wegetacyjnych i po jego zakończeniu był usuwany, w celu poboru próbek do dalszych analiz. W obrębie każdego bloku zaaplikowano 5 wariantów BioWAG oraz założono stanowiska kontrolne (bez dodatków). Każdy z wariantów wykonano w 18 powtórzeniach. Rzędy z poszczególnymi wariantami BioWAG rozmieszczono losowo.

Prototypy BioWAG przed umieszczeniem w glebie namaczano w wodzie wodociągowej do momentu całkowitego spęcznienia SAP. Na poletku doświadczalnym przygotowano otwory o średnicy 0,30 m. Ścianki otworów wyłożono syntetyczną osłoną, która zapewniła jednakową przestrzeń do rozwoju systemu korzeniowego oraz możliwość precyzyjnego porównywania parametrów biometrycznych roślin na wszystkich stanowiskach. Na dnie otworu umieszczono po jednym BioWAG danego typu, który następnie przysypano 0,15 m warstwą gleby. Na powierzchni wyznaczonych stanowisk równomiernie wysiano po 0,63 g nasion (zgodnie z zaleceniami producenta 200 kg/ha) odpowiednio dobranej mieszanki traw (65% *Lolium perenne*; 5% *Poa pratensis*; 20% *Festuca rubra*; 5% *Festuca ovina*) (**P2, P3, P4)**. Nawodnienia prowadzono wyłącznie we wczesnej fazie doświadczenia, tzn. do momentu wzejścia traw. Po tym okresie, zapas wody w BioWAG był wyłącznie uzależniony od opadów atmosferycznych. W analizowanym okresie nie stosowano dodatkowego nawożenia oraz środków ochrony roślin, niepożądane gatunki roślin usuwano ręcznie. Schemat pojedynczego stanowiska badawczego zaprezentowano na rysunku 1.



Rysunek 1. Schemat stanowiska badawczego: 1- syntetyczna osłona; 2- włóknina; 3- gleba; 4- superabsorbent polimerowy (SAP); 5- szkielet wewnętrzny **(P3)**

Glebę na obszarze badawczym sklasyfikowano jako piasek gliniasty **(P2, P3, P4)**. Szczegółową charakterystykę gleby przedstawiono w tabeli 1.

Tabela 1. Podstawowe parametry gleby **(P3)**

Parametr	Jednostka	Piasek gliniasty
pH	KCl 1M/dm^3	6,20 ± 0,06
N	g/kg gleby	0,53 ± 0,01
P	mg/100 g gleby	18,90 ± 0,56
K	mg/100 g gleby	5,60 ± 0,22
Mg	mg/100 g gleby	1,90 ± 0,04
Mn	mg/kg gleby	13,00 ± 0,39
Cu	mg/kg gleby	0,70 ± 0,02
Fe	mg/kg gleby	167,80 ± 5,43
Zn	mg/kg gleby	1,60 ± 0,04
Ciężar właściwy	g/cm^3	2,65
Gęstość nasypowa	g/cm^3	1,65
Porowatość	-	0,38
Materia organiczna gleby (SOM)	%	2,93

3.2.Materiały

➢ Szkielet wewnętrzny i superabsorbent polimerowy (SAP)

W badaniu zastosowano prototypy BioWAG składające się z trzech elementów: włókniny, szkieletu wewnętrznego oraz SAP. Wybrany SAP stanowił neutralny wobec środowiska kopolimer akrylamidu i akrylanu potasu (Aquasorb; SNF Floerger, Andrézieux, Francja), który jest powszechnie stosowany w aplikacjach środowiskowych (**P2, P3, P4**). Aquasorb stanowi suchy granulat, który pod wpływem wody przybiera formę przezroczystego żelu. Jest nietoksyczny oraz ulega powolnej biodegradacji pod wpływem oddziaływania wybranych czynników środowiskowych, w tym określonych bakterii naturalnie występujących w glebie (Oksińska i in. 2019; 2016). Wśród bakterii powodujących powolny rozkład SAP można wyróżnić m.in. *Enterococcus faecalis, Geobacillus thermoglucosidasius, Klebsiella pneumoniae, Variovorax boronicumulans, Kluyvera georgiana* i *Bacillus sphaericus* (Guezennec i in. 2015; Matsuoka i in. 2002).

Szkielet wewnętrzy został wykonany z drewna odpadowego, tworzącego przestrzenną ażurową konstrukcję, o wymiarach 0,20×0,20 m (**P2, P3, P4**).

➢ Włóknina

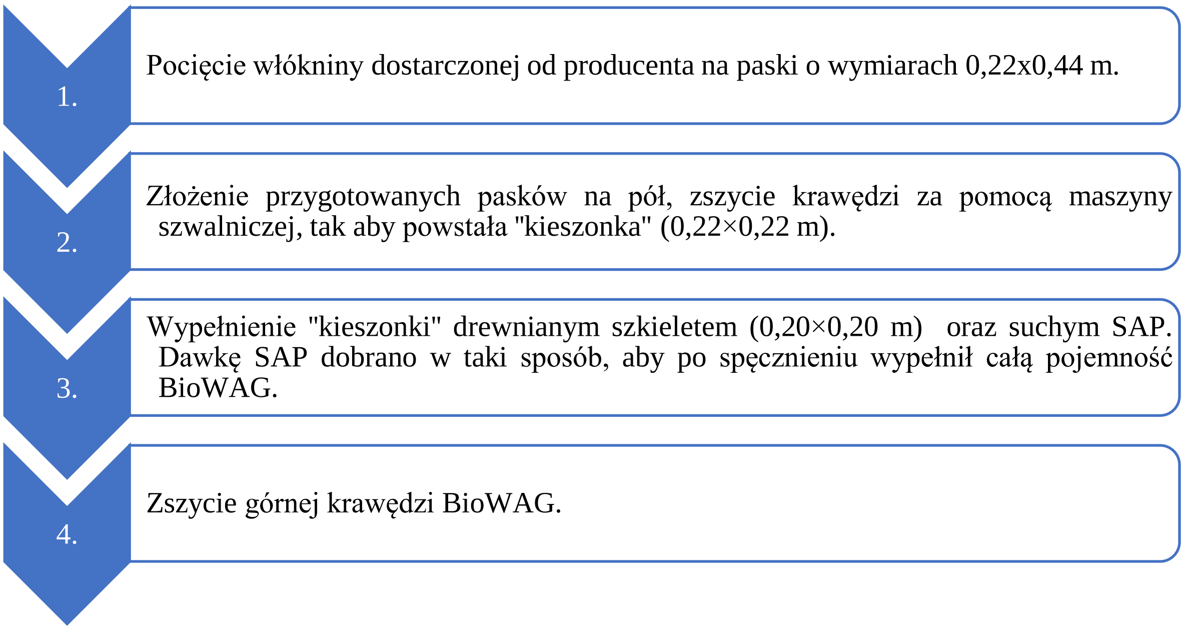
Do produkcji biodegradowalnych włóknin, stanowiących element BioWAG, zastosowano trzy rodzaje włókien naturalnych pochodzenia zwierzęcego i roślinnego: wełna, juta, len. Wyboru zastosowanych materiałów dokonano na podstawie przeglądu literatury (**P1**), dostępności materiałów oraz uwzględniając założenia gospodarki cyrkulacyjnej. Zastosowane w BioWAG włókniny stanowiły biodegradowalny materiał odpadowy. Wybrane parametry fizyko-chemiczne włóknin wzorcowych zamieszczono w tabeli 2 oraz opublikowano w artykule **P2**.

Tabela 2. Charakterystyka włóknin zastosowanych do produkcji BioWAG (**P2**)

Oznaczenie materiału	Skład włókniny, technologia produkcji	Fotografia próbki	Masa powierzchniowa [g/m^2]	Odporność na przebicie dynamiczne (stożek) [mm]	Odporność na przebicie statyczne (CBR) [N]
BA	99,4% wełna prana + 0,6% przeszycie syntetyczne; włóknina przeszywana		368	20	540
BB	100% wełna prana; włóknina igłowana		287	24	40
BC	90% wełna prana + 10% juta; włóknina igłowana		333	16	270
BD	90% wełna prana + 10% juta; włóknina przeszywana		289	23	620
BE	50% wełna prana + 50% len; włóknina igłowana		308	31	40

3.2.1. Produkcja prototypów

Prototypy BioWAG wyprodukowano w postaci przestrzennych mat o wymiarach 0,22 m na 0,22 m oraz wysokości 0,02 m. Etapy przygotowania prototypów przedstawiono na rysunku 2 (**P2, P3, P4**).



1. Pocięcie włókniny dostarczonej od producenta na paski o wymiarach 0,22x0,44 m.
2. Złożenie przygotowanych pasków na pół, zszycie krawędzi za pomocą maszyny szwalniczej, tak aby powstała "kieszonka" (0,22×0,22 m).
3. Wypełnienie "kieszonki" drewnianym szkieletem (0,20×0,20 m) oraz suchym SAP. Dawkę SAP dobrano w taki sposób, aby po spęcznieniu wypełnił całą pojemność BioWAG.
4. Zszycie górnej krawędzi BioWAG.

Rysunek 2. Schemat przygotowania prototypów BioWAG (**P3)**

3.3. Metody badawcze

3.3.1. Materiał roślinny

W celu scharakteryzowania materiału roślinnego wykonano oznaczenia:

- świeżej i suchej masy nadziemnych części traw;
- względnej zawartości wody (RWC - ang. *relative water content*) w częściach nadziemnych, wyznaczana jako stosunek aktualnej zawartości wody w tkankach do zawartości w tkankach w pełni nasyconych;
- składu chemicznego części nadziemnych traw, w tym określenie zawartości N, S, P oraz K. Azot całkowity oznaczono metodą analizy elementarnej z wykorzystaniem aparatu Elementar vario MACRO cube, natomiast ogólny poziom S metodą Buttersa-Chenery'ego. W celu oznaczenia zawartości: P, K materiał roślinny poddano suchej mineralizacji, a popiół rozpuszczono w kwasie azotowym. W uzyskanych roztworach po mineralizacji oznaczono fosfor metodą wanadowo-molibdenową oraz potas metodą fotometrii płomieniowej;
- długości, gęstości, oraz suchej masy sytemu korzeniowego.

Szczegółową metodykę przeprowadzonych analiz materiału roślinnego opublikowano w pracach **P3** i **P4**.

3.3.2. Materiał włókienniczy

Włókniny stanowiące element BioWAG poddano następującym badaniom:

- pomiar masy powierzchniowej wyznaczony za pomocą wagi analitycznej według PN-EN ISO 9864:2007;
- wyznaczenie grubości przy naciskach 2 kPa i 20 kPa, za pomocą grubościomierza stacjonarnego według PN-EN ISO 9863-1:2016-09;
- określenie odporności na przebicie statyczne (metoda CBR) wyznaczone za pomocą aparatu CBR według PN-EN ISO 12236:2007;
- oznaczenie odporności na dynamiczne przebicie wyznaczone metodą spadającego stożka zgodnie z normą PN-EN ISO 13433:2007;
- wyznaczenie wodoprzepuszczalności w kierunku prostopadłym do powierzchni wyrobu poprzez poddanie próbki przepływowi wody, skierowanemu prostopadle do jej powierzchni przy malejącej wysokości naporu hydraulicznego w oparciu o normę PN-EN ISO 11058:2019-07;
- oznaczenie składu chemicznego za pomocą spektroskopii w podczerwieni z transformacją Fouriera (FTIR). Zastosowano spektrofotometr FTIR „Thermo Scientific Nicolet iS5” z przystawką transmisyjną. Widma poddano obróbce matematycznej w celu uzyskania możliwości porównania jakościowego i ilościowego widm.

Szczegółową metodykę przeprowadzonych analiz materiału włókienniczego stanowiącego element BioWAG opublikowano w pracy **P2**.

3.3.3. Właściwości gleby

W losowo pobranej z poletka doświadczalnego glebie określono następujące parametry:

- skład granulometryczny, który wyznaczono za pomocą analizy sitowej. Badanie przeprowadzono na 500 g gleby w stanie powietrzno-suchym, którą przesiano przez zestaw sit o rozmiarze oczek: 0,10; 0,25; 0,50; 1,00; 2,00 i 5,00 mm. Dla drobniejszej frakcji przeprowadzono analizę areometryczną;
- zawartość materii organicznej oznaczono, jako procentowy ubytek masy po wypaleniu próbki w piecu w temperaturze 400 °C;
- gęstość objętościową szkieletu gruntowego wyznaczono na podstawie masy próbki o stałej objętości w stanie powietrzno-suchym;
- pH oznaczono metodą potencjometryczną,
- azot organiczny oznaczono metodą Kjeldahla,
- przyswajalne formy fosforu i potasu oznaczono metodą Egnera-Riehma,
- przyswajalne formy magnezu oznaczono metodą Schachtschabela,

- zawartość mikro- i makroelementów, takich jak Mn, Fe, Cu i Zn oznaczono metodą Rinkisa za pomocą spektrofotometru absorpcji atomowej AAS (Varian model SpectrAA 220FS, Varian Medical Systems, Inc., Charlottesville, VA, USA).

Szczegółową metodykę przeprowadzonych analiz właściwości gleby opublikowano w pracy **P3**.

3.3.4. Zdolności sorpcyjne SAP

Zdolności sorpcyjne SAP oznaczono zgodnie z tzw. metodą *tea bag method*. Badanie prowadzono po 5, 10, 30, 60, 120, 240 oraz 1440 minutach.

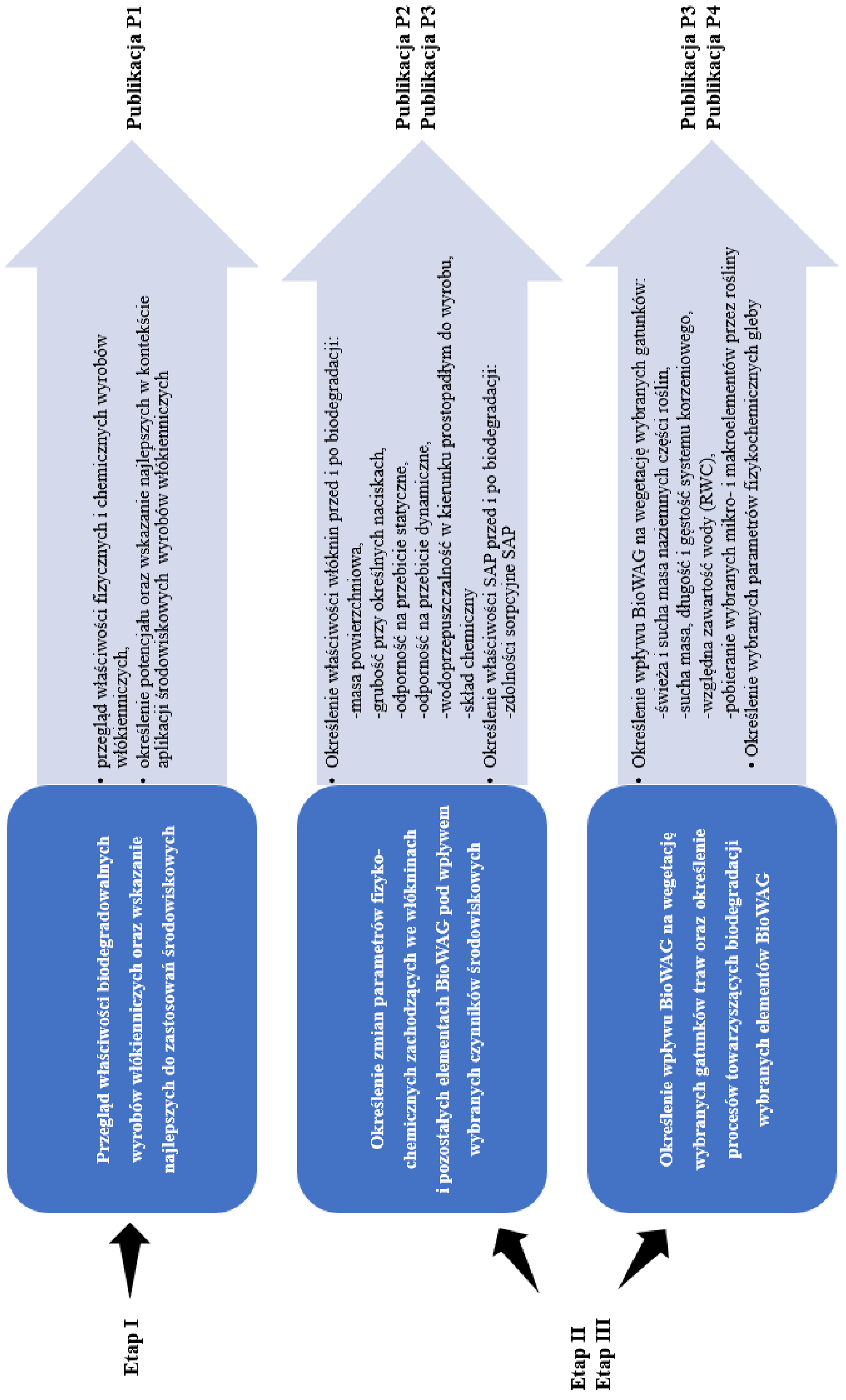
Szczegółową metodykę przeprowadzonych analiz zmian zdolności sorpcyjnych SAP zamieszczono w pracy **P3**.

3.3.5. Analiza statystyczna

Wyniki dotyczące materiału roślinnego poddano jednokierunkowej analizie wariancji. Przed przystąpieniem do analizy wariancji przeprowadzono testy jednorodności wariancji w obrębie grup za pomocą testu Levene'a oraz testu zgodności zmiennych z rozkładem normalnym Shapiro-Wilka. Istotność średnich różnic oceniono za pomocą testu post-hoc Tukeya z poziomem istotności p = 0,05 (**P3**). Ponadto, rozkład danych z uwzględnieniem wartości minimalnych, maksymalnych, mediany, dolnych i górnych kwartyli przedstawiono na wykresach pudełkowych (**P4**). Do analiz statystycznych zastosowano program statystyczny R (Team 2020) oraz Microsoft Excel 2019.

3.4. Etapy badań

Cele pracy osiągnięto w oparciu o trzy główne etapy badań zaprezentowane na rysunku 3, na którym przedstawiono organizację badań z uwzględnieniem zastosowanej metodyki.



Przegląd właściwości biodegradowalnych wyrobów włókienniczych oraz wskazanie najlepszych do zastosowań środowiskowych

- przegląd właściwości fizycznych i chemicznych wyrobów włókienniczych,
- określenie potencjału oraz wskazanie najlepszych w kontekście aplikacji środowiskowych wyrobów włókienniczych

Określenie zmian parametrów fizyko-chemicznych zachodzących we włókninach i pozostałych elementach BioWAG pod wpływem wybranych czynników środowiskowych

- Określenie właściwości włóknin przed i po biodegradacji:
  - -masa powierzchniowa,
  - -grubość przy określnych naciskach,
  - -odporność na przebicie statyczne,
  - -odporność na przebicie dynamiczne,
  - -wodoprzepuszczalność w kierunku prostopadłym do wyrobu,
  - -skład chemiczny
- Określenie właściwości SAP przed i po biodegradacji:
  - -zdolności sorpcyjne SAP

Określenie wpływu BioWAG na wegetację wybranych gatunków traw oraz określenie procesów towarzyszących biodegradacji wybranych elementów BioWAG

- Określenie wpływu BioWAG na wegetację wybranych gatunków:
  - -świeża i sucha masa naziemnych części roślin,
  - -sucha masa, długość i gęstość systemu korzeniowego,
  - -względna zawartość wody (RWC),
  - -pobieranie wybranych mikro- i makroelementów przez rośliny
- Określenie wybranych parametrów fizykochemicznych gleby

Rysunek 3. Organizacja badań nad trwałością biodegradowalnych geokompozytów sorbujących wodę

4. OMÓWIENIE I DYSKUSJA WYNIKÓW

4.1. Przegląd właściwości włókien biodegradowalnych

W pierwszym etapie pracy dokonano przeglądu literatury na temat włókien biodegradowalnych, stanowiących potencjalny materiał do produkcji włóknin stanowiących element BioWAG. Celem tego etapu było usystematyzowanie wiedzy dotyczącej właściwości dostępnych włókien biodegradowalnych, a następnie wskazanie najlepszych w zakresie aplikacji środowiskowych. Realizacja założeń tego etapu pozwoliła na wytypowanie włókien o właściwościach niezbędnych do opracowania prototypów BioWAG.

Wyniki pierwszego etapu badań przedstawiono w publikacji **P1**: **Marczak D.**, Lejcuś K., Misiewicz J., 2020, *Characteristics of biodegradable textiles used in environmental engineering: A comprehensive review*, Journal of Cleaner Production. DOI:10.1016/j.jclepro.2020.122129.

W publikacji **P1** szczegółowo opisano i przeanalizowano dane dotyczące najczęściej stosowanych włókien naturalnych (len, juta, konopie, kenaf, kokos, bawełna, palma, sizal, pszenica, ryż, bambus i wełna) oraz biopolimerów (PLA, PHA, PCL, PHB, PBS, CA). Usystematyzowano dostępną wiedzę na temat właściwości tych włókien, w tym scharakteryzowano źródło ich pochodzenia, parametry chemiczne i fizyczne, potencjalny czas biodegradacji w warunkach kontrolowanych i rzeczywistych. Dokonano również przeglądu dostępnych metod mechanicznej i chemicznej modyfikacji włókien roślinnych i zwierzęcych. Zidentyfikowano przyszłe trendy oraz kluczowe zagadnienia, które należy rozwiązać, aby umożliwić powszechne stosowanie materiałów biodegradowalnych w środowisku.

W przypadku wybranych zastosowań środowiskowych trwałość włóknin jest ważnym czynnikiem, aby mogły one spełniać określone funkcje przez lata. Jednak istnieje wiele zastosowań, w których pożądana jest aplikacja włóknin o znacznie krótszej żywotności. W literaturze dostępne są badania dotyczące geowłóknin biodegradowalnych, które mogą stanowić alternatywę dla włókien syntetycznych. Ze względu na wybrane właściwości, jednymi z najbardziej obiecujących są włókna juty, lnu i wełny (Kicińska-Jakubowska, Bogacz, Zimniewska 2012; Broda i in. 2017). Geowłókniny jutowe, ze względu na wysoką wytrzymałość, łatwość przetwarzania i aplikacji znalazły szeroki wachlarz zastosowań środowiskowych. Obecnie włókna juty są z powodzeniem stosowane w: inżynierii środowiska (element ochrony przeciwerozyjnej skarp, rekultywacja terenów zdegradowanych), ogrodnictwie i rolnictwie (zabezpieczenie systemu korzeniowego roślin, ochrona termiczna roślin, wspieranie wegetacji) (Gowthaman, Nakashima, Kawasaki 2018; Bordoloi, Garg, Sekharan 2017; Ghosh, Bhattacharyya, Mondal 2017; Chattopadhyay, Chakravarty 2009; Datta 2007). Z kolei Alimuzzaman i in. (2014) wskazują na szereg zalet włókien lnianych, które wyróżniają się dużą wytrzymałością na rozciąganie, nawet w wilgotnym środowisku, co czyni je atrakcyjnym materiałem w miejscach narażonych na kontakt z wodą. Kolejnym materiałem o dużym potencjale są włókniny na bazie wełny owczej. Badania Brody i in. (2020) oraz Böhme i in. (2012) wskazują, iż aplikacja wełny w glebie może pozytywnie wpłynąć na retencję glebową, ochronę termiczną roślin, a przede wszystkim stanowi źródło składników odżywczych łatwo dostępnych dla roślin.

Przeprowadzony przegląd literatury pozwolił na stwierdzenie, że wyżej wskazane włókna naturalne mają szczególne znaczenie w krótkoterminowych aplikacjach środowiskowych, gdzie zachowanie ich właściwości jest wymagane od jednego do trzech sezonów wegetacyjnych (Biswas i in. 2015; Sumi, Unnikrishnan, Mathew 2018; Broda i in. 2017). Dostępne badania dotyczące biodegradacji materiałów włókienniczych charakteryzują się dużą różnorodnością w zakresie ich właściwości chemicznych, mechanicznych oraz szacowanego czasu biodegradacji (Ramamoorthy, Skrifvars, Persson 2015). Większość badań prowadzonych jest w warunkach laboratoryjnych lub symulacyjnych. Przebieg procesu biodegradacji zależy od wielu czynników zewnętrznych, których rzeczywisty rozwój jest trudny lub niemożliwy do odtworzenia w warunkach kontrolowanych. Uwzględnienie tych parametrów w istotny sposób wpływa na stopień i czas biodegradacji włóknin. W związku z powyższym, wskazano na konieczność dalszych badań w warunkach rzeczywistych. Świadczy o tym również rosnąca ilość pojawiających się na rynku włóknin biodegradowalnych, które cieszą się zainteresowaniem, nie tylko wśród naukowców, ale także wśród praktyków. Jednak ze względu na ograniczoną wiedzę na temat przebiegu ich biodegradacji, znajdują one nadal mniejsze spektrum zastosowań.

Wyniki zaprezentowane w publikacji **P1** dostarczyły istotnych informacji niezbędnych do opracowania elementów BioWAG. Uwzględniając właściwości chemiczne, fizyczne, dostępność oraz aspekty ekonomiczne do produkcji włóknin stanowiących element BioWAG, wytypowano włókna wełny, juty oraz lnu.

4.2. Biodegradacja elementów BioWAG w warunkach rzeczywistych

W drugim etapie badań z wytypowanych włókien naturalnych wyprodukowano włókniny, które następnie zaimplementowano w BioWAG. Wykonane w kilku wariantach BioWAG zastosowano w doświadczeniu polowym. Celem tego etapu było określenie zmian parametrów fizyko-chemicznych zachodzących we włókninach i pozostałych elementach BioWAG pod wpływem wybranych czynników środowiskowych. Ponadto, przeanalizowano wybrane procesy towarzyszące biodegradacji zastosowanych materiałów oraz ich wpływ na wegetację roślin.

Wyniki drugiego etapu badań przedstawiono w publikacjach:

- **P2**: **Marczak D.**, Lejcuś K., Grzybowska-Pietras J., Biniaś W., Lejcuś I., Misiewicz J., 2020, *Biodegradation of sustainable nonwovens used in water absorbing geocomposites* *supporting plants vegetation*, Sustainable Materials and Technologies. 26: e00235. DOI:10.1016/j.susmat.2020.e00235;

- **P3: Marczak D.**, Lejcuś K., Kulczycki G., Misiewicz J., 2022. *Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility*. Science of the Total Environment. DOI:10.1016/j.scitotenv.2022.157169.

W zależności od technologii wytwarzania włóknin stanowiących element BioWAG, w publikacjach **P2** i **P3** zaobserwowano wyraźne różnice w stopniu i tempie ich biodegradacji. Po jednym sezonie wegetacyjnym wszystkie analizowane warianty włóknin (BA, BB, BC, BD, BE) uległy częściowej biodegradacji. W przypadku włóknin igłowanych (BB, BC, BE), niezależnie od rodzaju zastosowanego surowca, materiały już po 6 miesiącach eksploatacji w glebie, uległy silnej biodegradacji. Postęp degradacji włóknin igłowanych był na tyle zaawansowany, że materiał łatwo rozrywał się w ręku, a włókna stały się kruche i mało elastyczne. Na niektórych stanowiskach badawczych znaleziono trudne do wydzielenia resztki materiału. Taki stan próbek uniemożliwił wykonanie badań dotyczących właściwości fizycznych. Możliwe do określenia pozostały jedynie parametry chemiczne. Interesującym jest fakt, że mimo utraty integralności włóknin igłowanych, system korzeniowy traw rozwinął się na tyle dobrze, że swobodnie przerósł przez BioWAG, tworząc zwartą i wytrzymałą strukturę (rysunek 4).

Rysunek 4. System korzeniowy traw, który rozwinął się na włókninie igłowanej, 100% wełna (BB)

Wyznaczenie wybranych parametrów fizycznych było możliwe wyłącznie dla włóknin przeszywanych (BA, BD) (tabela 3). Ustalono, że włókniny przeszywane BA i BD, charakteryzowały się wyższą wytrzymałością i odpornością na degradację w porównaniu do włóknin igłowanych (**P2**).

Tabela 3. Parametry fizyczne włóknin zastosowanych w BioWAG przed i po procesie biodegradacji (**P2**)

Oznaczenie materiału	**Czas [miesiące]**	**Masa powierzchniowa [g/m^2]**	**Grubość [mm]**		**Odporność na przebicie dynamiczne (stożek) [mm]**	**Odporność na przebicie statyczne (CBR) [N]**
			2kPa	**20kPa**		
BA	0	368	2,4	1,6	20	540
	6	57	1,1	0,8	33	140
BB	0	287	3,3	1,5	24	40
	6	-	-	-	-	-
BC	0	333	3,5	1,9	16	270
	6	-	-	-	-	-
BD	0	289	2,3	1,5	23	620
	6	134	1,2	0,7	37	200
BE	0	308	2,9	1,5	31	40
	6	-	-	-	-	-

Analiza parametrów fizycznych włóknin przeszywanych (wzorcowych oraz po 6 miesiącach eksploatacji w glebie), pozwoliła na oszacowanie stopnia ich biodegradacji w glebie. Największą redukcję masy powierzchniowej wynoszącą ponad 84% odnotowano dla włókniny BA. W przypadku włókniny BD po okresie 6 miesięcy od zainstalowania w glebie, zaobserwowano ubytek masy powierzchniowej o 54%. Obie włókniny przeszywane charakteryzowały się zbliżoną grubością przed i po biodegradacji. Z kolei odporność na statyczne przebicie (metoda CBR) dla włókniny BA uległa zmniejszeniu o 75%, natomiast dla włókniny BD o 68%. Niezależnie od rodzaju zastosowanego surowca odporność na dynamiczne przebicie metodą spadającego stożka była zbliżona i wzrosła o ponad 60%. Badanie właściwości filtracyjnych włóknin pobranych z poletka doświadczalnego, było również możliwe wyłącznie dla włóknin przeszywanych. W przypadku włókniny BA początkowa wodoprzepuszczalność prostopadła wynosiła 74,7 mm/s, natomiast po określonym okresie badawczym zdolność przepływu wody przez włókninę wzrosła o 43%. Z kolei wodoprzepuszczalność włókniny przeszywanej BD wzrosła o około 60% (**P2**).

Z uwagi na zastosowanie spektroskopii w podczerwieni z transformacją Fouriera (FTIR), badanie składu chemicznego włóknin, było możliwe zarówno dla włóknin igłowanych, jak i przeszywanych. Analiza porównawcza widm FTIR próbek kontrolnych i pobranych z poletka doświadczalnego, potwierdziły badania dostępne w literaturze, z których wynika, że wraz z postępującą biodegradacją wełny, białko keratyny przekształca się w biomasę możliwą do wchłonięcia przez system korzeniowy roślin (Broda i in. 2016; Janardhnan, Sain 2011). Biodegradacja analizowanych materiałów była przede wszystkim spowodowana obecnością enzymów wydzielanych przez mikroorganizmy glebowe. Po degradacji struktury naskórka, enzymy przenikały do wnętrza włókna, powodując jego stopniowy rozkład, co było widoczne na wszystkich analizowanych widmach FTIR. Analiza kształtu widm przed i po biodegradacji, wskazywała na rozluźnienie struktury międzycząsteczkowej (**P2**). Zaobserwowane mechanizmy potwierdzały stopniowe uwalnianie składników bogatych w N z zachowaniem charakterystycznej budowy chemicznej keratyny. Również Lal i in. (2020) zaobserwowali wyraźny wzrost żyzności gleby w N oraz wyższą aktywność enzymów po aplikacji wełny w glebie. Z kolei, biodegradacja składnika roślinnego (juty i lnu) przebiegała w mechanizmie degradacji łańcucha celulozowego. Intensywny rozkład włókien zastosowanych w BioWAG mógł wynikać z bezpośredniego kontaktu włókniny z SAP. Badania Oksińskiej i in. (2019) dotyczące biodegradacji SAP obecnego w WAG wskazują, na intensywną kolonizację bakterii i grzybów, które powodują jego stopniową degradację i jednocześnie mogą osadzać się na włókninie.

Badania FITR wykazały biologiczną aktywność składników uwalnianych z włókien i ich dostępność w przynajmniej kolejnym sezonie wegetacyjnym. Wyniki składu chemicznego gleby zaprezentowane w pracy **P3** potwierdzają, iż BioWAG zachowały swoją skuteczność w zakresie wspomagania wegetacji przez trzy sezony wegetacyjne. Na stanowiskach z BioWAG zaobserwowano wyraźny wzrost żyzności gleby. Najistotniejsze różnice w składzie chemicznym odnotowano dla fosforu, którego zawartość po trzech sezonach wegetacyjnych była wyższa od 26 do 81% w porównaniu do stanowisk kontrolnych. Istotne różnice zaobserwowano również w przypadku azotu i magnezu. Zastosowanie BioWAG nie wpłynęło istotnie na pH gleby.

W publikacji **P3** określono również redukcję zdolności sorpcyjnych SAP w czasie. W literaturze opisywanych jest szereg czynników, które mogą negatywnie wpłynąć na właściwości SAP, są to m.in. obciążenie glebą, zasolenie, temperatura, pH gleby, obecności jonów jedno- i wielowartościowych, czy mikroorganizmów glebowych (Lejcuś i in. 2015; Nascimento i in. 2021; Guezennec i in. 2015). Zastosowanie szkieletu wewnętrznego w konstrukcji BioWAG pozwoliło na ograniczenie negatywnego oddziaływania jednego z zasadniczych czynników, czyli obciążenia glebą. Dzięki czemu możliwe było osiągnięcie bardzo wysokiej skuteczności technologii w pierwszym sezonie wegetacyjnym. Maksymalna chłonność wzorcowego SAP wynosiła około 270 g/g. Po pierwszym roku zaobserwowano największy spadek zdolności sorpcyjnych SAP, który wyniósł ponad 70%. Po kolejnym roku eksploatacji w podłożu nie zaobserwowano tak dynamicznych zmian, a redukcja zdolności sorpcyjnych wynosiła około 75% w porównaniu do wzorca. Po trzech latach SAP zachował zaledwie 17% pierwotnej chłonności. Spadek zdolności sorpcyjnych mógł być podyktowany m.in. intensywną biodegradacją szkieletu wewnętrznego i stopniową biodegradacją SAP. Szkielet wewnętrzny stanowiący element BioWAG, wykonano z niskiej jakości drewna odpadowego, które uległo intensywnej biodegradacji po pierwszym sezonie wegetacyjnym (rysunek 5). Po tym okresie szkielet stał się kruchy, łamliwy i utracił swoją integralność, co mogło wpłynąć na zwiększone obciążenie SAPu glebą. Ponadto wcześniejsze badania Oksińskiej i in. (2016) dotyczące właściwości SAP zaaplikowanego w WAG potwierdziły jego stopniową biodegradację w glebie. Zaobserwowano, że po dziewięciu miesiącach eksploatacji w glebie, SAP utracił około 35% zdolności sorpcyjnych oraz ponad 30% suchej masy. W literaturze dostępnych jest wiele badań na temat wykorzystania kopolimeru akrylamidu i akrylanu potasu, jako źródła azotu lub węgla przez wybrane bakterie glebowe (Guezennec i in. 2015). Stwierdzono, że wybrane bakterie naturalnie występujące w glebie takie jak: *Enterococcus faecalis, Geobacillus thermoglucosidasius, Klebsiella pneumoniae, Variovorax boronicumulans, Kluyvera georgiana* i *Bacillus sphaericus* mogą skutecznie degradować SAP (Guezennec i in. 2015; Matsuoka i in. 2002).

Stan BioWAG przed biodegradacją

Stan BioWAG po sześciu miesiącach eksploatacji

Rysunek 5. Poglądowy stan BioWAG przed oraz po biodegradacji

Uzyskane wyniki badań wskazują, iż w przypadku krótkoterminowych zastosowań (np. obejmujących jeden sezon wegetacyjny), do produkcji BioWAG dobrze sprawdzą się włókniny na bazie włókien naturalnych wytwarzane techniką igłowania, które uległy intensywnej biodegradacji w trakcie pierwszego sezonu wegetacyjnego. W przypadku zastosowań obejmujących kilka sezonów wegetacyjnych (np. dwa-trzy sezony), skuteczniejszym rozwiązaniem mogą okazać się włókniny przeszywane, które charakteryzowały się lepszymi właściwości mechanicznymi. Niemniej jednak, niezależnie od technologii wytwarzania i składu surowcowego, wytypowane włókniny charakteryzowały się wystarczającą trwałością do utrzymania wegetacji i prawidłowego funkcjonowania BioWAG, przez co najmniej jeden sezon wegetacyjny. Zastosowanie naturalnych materiałów pozytywnie wpłynęło na wzrost roślin, a przede wszystkim stanowiło przyjazne dla środowiska rozwiązanie.

4.3.Określenie wpływu BioWAG na wegetację wybranych gatunków traw

Poszukiwanie skutecznych rozwiązań oraz strategii ochrony roślin przed zmianami klimatu, skutkami suszy i utratą żyzności gleb są obecnie jednymi z bardziej pożądanych i przyszłościowych kierunków badań. BioWAG stanowią odpowiedź na zidentyfikowane problemy środowiskowe. Technologia została opracowana, jako innowacyjny dodatek doglebowy wspomagający wegetację roślin oraz oszczędzanie wody. Trzeci etap badań, który prowadzono równolegle do drugiego dotyczył określania wpływu BioWAG na wegetację wybranych gatunków traw.

Głównymi celami tego etapu badań było określenie wpływu BioWAG na wegetację wybranych gatunków traw oraz procesów towarzyszących biodegradacji wybranych elementów BioWAG, m.in. zidentyfikowanie mikro- i makroelementów uwalnianych do gleby oraz efektywnie pobieranych przez rośliny.

Wyniki trzeciego etapu badań przedstawiono w publikacjach:

- **P3: Marczak D.**, Lejcuś K., Kulczycki G., Misiewicz J. 2022. *Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility*. Science of the Total Environment. DOI:10.1016/j.scitotenv.2022.157169;
- **P4: Marczak D.**, Lejcuś K, Lejcuś I., Misiewicz J. 2023. *Sustainable Innovation: Turning Waste into Soil Additives.* Materials. DOI:10.3390/ma16072900.

W publikacjach **P3** oraz **P4** przeanalizowano wpływ BioWAG na wegetację wybranych gatunków traw. Badania prowadzono w warunkach rzeczywistych przez trzy sezony wegetacyjne, co pozwoliło kompleksowo ocenić skuteczność tej technologii. Na stanowiskach z BioWAG darnina tworzyła gęstą, zwartą strukturę o intensywnie zielonej barwie, w przeciwieństwie do stanowisk kontrolnych. Największe różnice między stanowiskami z BioWAG, a kontrolą były widoczne podczas dwóch pierwszych sezonów wegetacyjnych (lata 2018-2019) (rysunek 6).

Rysunek 6. Stanowiska doświadczalne z widocznymi różnicami między próbami kontrolnymi, a próbkami rosnącymi na BioWAG (**P3**)

Wyniki przedstawione w publikacjach **P3** i **P4** wskazują na bardzo wysoką skuteczność opracowanej technologii, w porównaniu do tradycyjnej metody aplikacji SAP (poprzez bezpośrednie mieszanie z glebą) lub innych dodatków doglebowych. Eneji i in. (2013) ocenili potencjał SAP przy trzech poziomach nawadniania. Zastosowanie SAP przy nawodnieniu deficytowym zwiększyło biomasę kukurydzy o blisko 100% oraz o około 40% przy nawadnianiu umiarkowanym. Z kolei Rodionov i in. (2012) w dwuletnim doświadczeniu polowym przeanalizowali wpływ hydrożelu wymieszanego z dodatkami na rozwój *Dactylis glomerata L.* W zależności od zastosowanego wariantu, po pierwszym roku doświadczenia zanotowano około 90% przyrost nadziemnych części roślin, jednak nie stwierdzono istotnych różnic w rozwoju systemu korzeniowego. W przypadku zastosowania BioWAG odnotowano zwiększenie przyrostów świeżej masy traw już w pierwszym roku doświadczenia od 240 do 430%, w porównaniu do stanowisk kontrolnych. W kolejnych latach przyrosty świeżej masy traw były wyższe o 200-300% (2019) oraz 40-55% (2020) (tabela 4).

Tabela 4. Średni przyrost świeżej i suchej masy traw w latach 2018–2020; Wartości oznaczone tą samą literą nie różnią się istotnie (a = 0,05), (**P3**)

Oznaczenie stanowiska	I rok		II rok		III rok	
	Świeża masa [g]	Sucha masa [g]	Świeża masa [g]	Sucha masa [g]	Świeża masa [g]	Sucha masa [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

Dodatek BioWAG wpłynął pozytywnie na intensywny rozwój systemu korzeniowego na wszystkich analizowanych stanowiskach (rysunek 7). Najlepsze efekty ponownie zanotowano podczas pierwszego sezonu wegetacyjnego, kiedy sucha masa oraz gęstość systemu korzeniowego były wyższe od 130 do 220% w porównaniu do kontroli. W kolejnych latach parametry te były wyższe od 120 do 186% (2019) oraz od 73 do 120% (2020). Zastosowanie BioWAG miało również pozytywny wpływ na inne parametry sytemu korzeniowego tj. na długość i gęstość długości korzeni (RLD). Średnia długość oraz wskaźnik RLD systemu korzeniowego traw były odpowiednio wyższe o 17-36% (2018), 24-32% (2019) i 24-38% (2020) w porównaniu do stanowisk kontrolnych. Pozytywny wpływ BioWAG na wzrost roślin ma zasadnicze znaczenie w perspektywie ich aplikacji na obiektach inżynierskich, takich jak wały przeciwpowodziowe i nasypy drogowe, gdzie obecność dobrze rozwiniętego systemu korzeniowego traw stanowi podstawę skutecznie działającego ubezpieczenia biotechnicznego. Ponadto dobrze rozwinięty system korzeniowy sprzyja wykorzystaniu wody dostępnej w głębszych warstwach profilu glebowego i optymalnemu rozwojowi roślin w kolejnych sezonach wegetacyjnych, nawet w przypadku całkowitej biodegradacji BioWAG.

Rysunek 7. System korzeniowy traw z widocznymi różnicami między próbami kontrolnymi, a próbkami rosnącymi na BioWAG (**P3**)

Wysoka skuteczność BioWAG wynika również z połączenia zdolności retencyjnych SAP z biodegradowalnymi materiałami odpadowymi. Wyniki przedstawione w pracach **P3** i **P4** wskazują, iż zastosowanie biodegradowalnych włóknin odegrało istotną rolę w dostarczaniu roślinom składników odżywczych. Powolna degradacja włóknin sprawiła, że BioWAG w okresie trzech lat stopniowo uwalniały do podłoża składniki odżywcze, a ich funkcjonowanie można porównać do nawozów o spowolnionym działaniu. Najwyższą skuteczność BioWAG zanotowały w pierwszym sezonie, kiedy włókniny uległy intensywnej biodegradacji. W tym okresie rośliny wykazywały najwyższy pobór wybranych mikro- i makroelementów. Na stanowiskach z BioWAG pobór azotu był wyższy o 178–513% w porównaniu do kontroli. Istotne różnice odnotowano również dla siarki (wzrost o 300-450%), fosforu (wzrost o 250-450%) i potasu (wzrost o 277-508%). W trakcie drugiego i trzeciego sezonu wegetacyjnego obserwowano powolny spadek skuteczności BioWAG, co było związane ze stabilizacją procesu biodegradacji. Niemniej jednak, w tym okresie na stanowiskach z BioWAG nadal zaobserwowano wyższy pobór wybranych mikro- i makroelementów. Co więcej, BioWAG wpłynęły na ograniczenie skutków stresu wywołanego ograniczonym dostępem do wody, który był zauważalny na stanowiskach kontrolnych. Potwierdzeniem tych obserwacji jest utrzymanie przez trzy sezony wegetacyjne wyższych nawet o 30% wartości wskaźnika RWC w porównaniu do stanowisk kontrolnych.

Przedstawione wyniki badań dają podstawę do wdrożenia rozwiązania, które pozwala zredukować dawkę nawodnień oraz nawozów niezbędnych do prawidłowego rozwoju wybranych gatunków roślin, przy jednoczesnym spełnieniu założeń gospodarki cyrkulacyjnej oraz zasad zrównoważonego rozwoju. Opisane w pracy aspekty dają podstawę do dalszego promowania zrównoważonych technologii oraz racjonalnego wspomagania wegetacji roślin przy jednoczesnej dbałości o środowisko.

5. PODSUMOWANIE I WNIOSKI

W ostatnich latach problemy dotyczące niedoboru wody, utraty żyzności gleb oraz zanieczyszczenia środowiska zyskują na znaczeniu. Zjawiska te mają szereg negatywnych skutków widocznych nie tylko w rolnictwie, ale także w inżynierii środowiska, gdzie rośliny stanowią istotny element ubezpieczenia biotechnicznego budowli ziemnych. Jednym z zasadniczych elementów przeciwdziałania tym negatywnym zjawiskom i adaptacji do zmian klimatu jest poszukiwanie, a następnie wdrażanie nowych technologii zgodnych z założeniami zrównoważonego rozwoju. Mając na uwadze zidentyfikowane problemy oraz obecne trendy zbadano oraz sprawdzono skuteczność innowacyjnej technologii w postaci biodegradowalnego geokompozytu sorbującego wodę.

Wyniki przedstawione w niniejszym cyklu publikacyjnym rozprawy doktorskiej pozwoliły na **potwierdzenie postawionej hipotezy badawczej**, udowadniając, że zastosowanie materiałów biodegradowalnych w postaci włóknin na bazie naturalnych włókien, umożliwia ich stopniową biodegradację w glebie przy jednoczesnym wspomaganiu wegetacji wybranych gatunków traw (**H1**).

Realizacja celów głównych i szczegółowych, przegląd literatury oraz przeprowadzone badania laboratoryjne i terenowe pozwoliły na sformułowanie następujących wniosków:

1. Biodegradowalne materiały włókiennicze mają duży potencjał aplikacyjny m.in. w inżynierii środowiska, rolnictwie oraz ogrodnictwie. Uwzględniając właściwości fizyczne, chemiczne, dostępność surowca oraz aspekty ekonomiczne do produkcji włóknin stanowiących element BioWAG, wskazano odpadowe włókna wełny, juty i lnu (**P1**).
2. We wszystkich wariantach BioWAG zaobserwowano spadek parametrów fizyko-chemicznych elementów BioWAG już po 6 miesiącach eksploatacji w glebie. W tym okresie włókniny igłowane utraciły swoją integralność, co uniemożliwiło wyznaczenie ich parametrów fizycznych. W przypadku włóknin przeszywanych zanotowano spadek wybranych parametrów fizycznych, m.in. redukcję masy powierzchniowej o ponad 84% dla włókniny BA oraz o 54% dla włókniny BD (**P2**).
3. Uzyskane wyniki badań wskazują, iż w przypadku krótkoterminowych aplikacji, dobrze sprawdzą się włókniny wytwarzane techniką igłowania, które uległy intensywnej biodegradacji w trakcie pierwszego sezonu wegetacyjnego. W przypadku aplikacji obejmujących kilka sezonów wegetacyjnych, skuteczniejszym rozwiązaniem mogą okazać się włókniny przeszywane, które wykazują lepsze właściwości mechaniczne oraz wyższą odporność na biodegradację (**P2**).

4. Niezależnie od technologii wytwarzania i składu surowcowego, zastosowane włókniny charakteryzowały się trwałością pozwalającą na utrzymanie wegetacji i prawidłowego funkcjonowania BioWAG, przez co najmniej jeden sezon wegetacyjny. Czas biodegradacji był odpowiedni do prawidłowego rozwoju wybranych gatunków traw (**P2, P3, P4**).
5. Na stanowiskach z BioWAG zaobserwowano wzrost żyzności gleby. Po trzech sezonach wegetacyjnych, w zależności od zastosowanego wariantu BioWAG, zawartość P była wyższa w porównaniu do kontroli od 26 do 81% oraz N od 15 do 70%. Działanie BioWAG można porównać do nawozów o spowolnionym działaniu (**P3**).
6. Składniki odżywcze uwalniane do gleby przez BioWAG były łatwo dostępne dla roślin. Przez trzy kolejne sezony wegetacyjne trawy charakteryzowały się istotnie wyższymi poborami wybranych mikro- i makroelementów (N, P, S, K) z gleby (**P3**).
7. Aplikacja BioWAG pozytywnie wpłynęła na wegetację wybranych gatunków traw. W zależności od zastosowanego wariantu BioWAG przyrosty świeżej masy nadziemnych części traw były wyższe: w I sezonie wegetacyjnym od 240 do 430%, w II sezonie wegetacyjnym od 200 do 300% oraz w III sezonie wegetacyjnym od 40 do 55% w porównaniu do kontroli (**P3, P4**).

8. Zastosowanie BioWAG sprzyjało intensywnemu rozwojowi systemu korzeniowego oraz ograniczeniu stresu wodnego wybranych gatunków traw. W zależności od zastosowanego wariantu BioWAG przyrosty suchej masy systemu korzeniowego traw były wyższe: w I sezonie wegetacyjnym od 130 do 220%, w II sezonie wegetacyjnym od 120 do 186% oraz w III sezonie wegetacyjnym od 73 do 120% w porównaniu do kontroli. Podczas trzech sezonów wegetacyjnych wartości wskaźnika RWC utrzymywały się na wyższym poziomie w porównaniu do stanowisk kontrolnych (**P3, P4**).

9. Przedstawione wyniki dają podstawę do wdrożenia rozwiązania, które pozwala zredukować dawkę nawodnień oraz nawozów niezbędnych do prawidłowego rozwoju wybranych gatunków traw, przy jednoczesnym uwzględnieniu założeń gospodarki cyrkulacyjnej oraz zasad zrównoważonego rozwoju (**P2, P3, P4**).

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Normy:

1. PN-EN ISO 9864:2007 Geosyntetyki - Metoda badania dotycząca wyznaczania masy powierzchniowej geotekstyliów i wyrobów pokrewnych.
2. PN-EN ISO 9863-1:2016-09 Geosyntetyki - Wyznaczanie grubości przy określonych naciskach - Część 1: Warstwy pojedyncze.
3. PN-EN ISO 12236:2007 Geosyntetyki - Badanie na przebicie statyczne (badanie CBR).
4. PN-EN ISO 13433:2007 Geosyntetyki - Badanie dynamicznego przebicia (metoda spadającego stożka)
5. PN-EN ISO 11058:2019-07 Geotekstylia i wyroby pokrewne - Wyznaczanie charakterystyk wodoprzepuszczalności w kierunku prostopadłym do powierzchni wyrobu, bez obciążenia.

DOROBEK NAUKOWY

Wykształcenie:

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02.2017-06.2018	**Uniwersytet Przyrodniczy we Wrocławiu** **Studia magisterskie**, stacjonarne, Wydział Inżynierii Kształtowania Środowiska i Geodezji; Kierunek: inżynieria i gospodarka wodna; Specjalizacja: zagospodarowanie wód opadowych
10.2013-02.2017	**Uniwersytet Przyrodniczy we Wrocławiu** **Studia inżynierskie**, stacjonarne, Wydział Inżynierii Kształtowania Środowiska i Geodezji; Kierunek: inżynieria i gospodarka wodna

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15.11.2022-15.11.2024	**Kierownik projektu – Preludium 20, Narodowe Centrum Nauki,** projekt nr 2021/41/N/ST10/01013, pt. *Badanie procesów biodegradacji geotekstyliów z włókien naturalnych i dodatków wspomagających wegetację roślin stosowanych w inżynierii środowiska*
01.10.2022-30.09.2023	**Starszy technik – Horyzont Europa,** projekt nr 101060361, pt. *SYMBIOREM - Symbiotic, circular bioremediation systems and biotechnology solutions for improved environmental, economic and social sustainability in pollution control*
22.10.2021-30.09.2022	**Wykonawca – Program Rozwoju Obszarów Wiejskich 2014-2020 -** projekt nr 00032.DDD.6509.00013.2019.07, pt. *Innowacyjna technologia produkcji sadzonek roślin jagodowych typu plug plant i long cane o wysokim współczynniku produktywności na przykładzie maliny i jeżyny bezkolcowej*
01.10.2020-31.03.2022	**Wykonawca – Program Rozwoju Obszarów Wiejskich 2014-2020 -** projekt nr 00018.DDD.6509.00088.2018.09, pt. *Dostosowanie i wdrożenie innowacyjnej technologii uzdatniania wody w zamkniętym systemie nawadniania wraz z wykorzystaniem biologicznych środków ochrony i biostymulatorów na przykładzie żurawiny wielkoowocowej*
01.07.2018-30.09.2021	**Wykonawca – Narodowe Centrum Badań i Rozwoju,** projekt nr POIR.04.01.04-00-0061/16, pt. *Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin*

Doświadczenie zawodowe:

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03.2021-04.2022	**Współautor, opracowanie merytoryczne –** opracowanie pt. *Strategia Gospodarowania Wodami Opadowymi i Roztopowymi w Poznaniu.* 2022. Poznań.
10.2018-12.2019	**Współautor, opracowanie merytoryczne –** opracowanie pt. *Katalog Dobrych Praktyk cz. II Zasady zrównoważonego gospodarowania wodami opadowymi na obszarze zabudowanym.* 2019. Wrocław.
01.07.2016-31.08.2016	**Praktyka zawodowa – Starostwo Powiatowe w Sieradzu**

Staże i szkolenia naukowe:

05.08.2019-09.08.2022	**Szkolenie z zakresu badań geotekstyliów i wyrobów włókienniczych**; Laboratorium Geosyntetyków i Wyrobów Włókienniczych, Wydział Inżynierii Materiałów, Budownictwa i Środowiska Akademii Techniczno-Humanistycznej w Bielsku-Białej
20.11.2019-22.11.2019	**Warsztaty szkoleniowe - Zastosowanie geosyntetyków i tekstyliów technicznych w obiektach inżynierskich**, Ustroń

Nagrody i wyróżnienia:

07.2023-obecnie	**Laureat programu START 2023 – STYPENDIA DLA MŁODYCH UCZONYCH, Fundacji na rzecz Nauki Polskiej (FNP)** ***Stypendysta korzystający ze wsparcia finansowego Fundacji na rzecz Nauki Polskiej (FNP)***
11.2022-06.2023	**Laureat stypendium dla doktorantów za osiągnięcia w dziedzinie nauk inżynieryjno-technicznych w Studenckim Programie Stypendialnym Studencki**, przyznane przez Komisję Stypendium im. Mariana Suskiego. Program Stypendialny realizowany z inicjatywy Prezydenta Wrocławia. 2022. Wrocław
15.11.2021	**Wyróżnienie za osiągnięcia w dziedzinie nauk inżynieryjno-technicznych w Studenckim Programie Stypendialnym**, przyznane przez Komisję Stypendium im. Mariana Suskiego. Program Stypendialny realizowany z inicjatywy Prezydenta Wrocławia. 2021. Wrocław
10.2020-09.2023	**Beneficjent Stypendium Rektora dla najlepszych doktorantów i Stypendium Doktoranckiego z dotacji na zadania projakościowe,** Uniwersytet Przyrodniczy we Wrocławiu

Wykaz dorobku naukowego:

Lp.	Publikacja	Punkty MNiSW	IF
1	**Marczak D.**, Lejcuś K., Lejcuś I., Misiewicz J. 2023. *Sustainable Innovation: Turning Waste into Soil Additives.* Materials. 16, 2900. DOI:10.3390/ma16072900	140	3,400
2	Misiewicz, J., Sankar Datta, S., Lejcuś, K.L., **Marczak, D.**, 2022. *The Characteristics of Time-Dependent Changes of Coefficient of Permeability for Superabsorbent Polymer-Soil Mixtures*. Materials. 2022, 15, 4465 https://doi.org/10.3390/MA15134465	140	3,400
3	**Marczak D.**, Lejcuś, K., Kulczycki, G., Misiewicz, J. 2022. *Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility*. Science of the Total Environment. 844, 157169. DOI:10.1016/j.scitotenv.2022.157169	200	9,800
4	Misiewicz J., Głogowski A., Lejcuś K., **Marczak D.** 2020. *The Characteristics of Swelling Pressure for Superabsorbent Polymer and Soil Mixtures*. Materials. 13 (22), 5071. DOI:10.3390/ma13225071	140	3,623
5	**Marczak D.**, Lejcuś K., Grzybowska-Pietras J., Biniaś W., Lejcuś I., Misiewicz J. 2020. *Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation*. Sustainable Materials and Technologies. 26, e00235. DOI:10.1016/j.susmat.2020.e00235	200	7,053
6	**Marczak D.**, Lejcuś K., Misiewicz J. 2020. *Characteristics of biodegradable textiles used in environmental engineering: a comprehensive review*. Journal of Cleaner Production. 268, 122129. DOI:10.1016/j.jclepro.2020.122129	140	9,297
7	Misiewicz J., Lejcuś K., Dąbrowska J. **Marczak D.**, 2019. *The Characteristics of Absorbency Under Load (AUL) for Superabsorbent and Soil Mixtures*. Scientific Reports. 9, 18098. doi:10.1038/s41598-019-54744-4	140	3,998
8	**Marczak D.**, Burszta-Adamiak E. 2018., *Ocena ilości i dynamiki odpływu z ekstensywnych dachów zielonych*, INSTAL, 7/8, 38-42	7	-

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Konferencje:

1. **Marczak D.**, Lejcuś K., Misiewicz J. *Biodegradowalne geotekstylia wspomagające wegetację roślin stosowanych w inżynierii środowiska*. VII Ogólnopolski Kongres Inżynierii Środowiska. Kazimierz Dolny, 2023
2. Oksińska M., Magnucka E., Kmieć A., **Marczak D.**, Pietr S., Lejcuś K. *Wykorzystanie geokompozytu sorbującego wodę w uprawie tawulca pogiętego.* IV Ogólnopolska Konferencja Naukowa „Problemy ochrony roślin na terenach zurbanizowanych", Wrocław, 2023
3. **Marczak D.**, Lejcuś K., Misiewicz J. *Możliwości wykorzystania hydrożeli w technologii produkcji sadzonek roślin jagodowych typu plug plant i long cane o wysokim współczynniku produktywności na przykładzie maliny*. Konferencja podsumowująca realizację operacji pt. Innowacyjna technologia produkcji sadzonek roślin jagodowych typu plug plant i long cane o wysokim współczynniku produktywności na przykładzie maliny i jeżyny bez kolcowej. Bratoszewice, 2022
4. Lejcuś K., **Marczak D.**, Misiewicz J., Śpitalniak M. Biodegradable water absorbing geocomposites (BioWAG) - the novel solution for greening of cities and nature based solutions. Urban Transitions. 8-10.10. Spain, 2022
5. **Marczak D.**, Lejcuś K. *Sustainable Water Storage Technology Based On Biodegradable Waste Materials.* Proceedings of the 8th World Congress on New Technologies (NewTech'22). Prague, Czech Republic, 2022. DOI: 10.11159/icepr22.177
6. **Marczak D.**, Lejcuś K., Misiewicz J. *Geokompozyty sorbujące wodę – zrównoważona technologia wspomagająca wegetację roślin i oszczędzanie wody*. VII Konferencja Naukowo-Techniczna: Nowe kierunki badań w inżynierii środowiska, energetyce, geodezji i gospodarce przestrzennej. Zwierzyniec, 2021
7. **Marczak D.,** Lejcuś K., Misiewicz J. *Biodegradowalne geokompozyty sorbujące wodę wspomagające wegetację roślin*. XXI Konferencja naukowo-techniczna geosyntetyki i tekstylia techniczne w budownictwie i ochronie środowiska. Ustroń, 2019
8. Lejcuś K., Dąbrowska J., Śpitalniak M., **Marczak D.**, Misiewicz J. *Możliwości zastosowania biodegradowalnych geokompozytów sorbujących wodę w inżynierii środowiska,* V Konferencja Naukowo-Techniczna: Nowe kierunki badań w inżynierii środowiska, energetyce, geodezji i gospodarce przestrzennej. Krynica-Zdrój, 2019
9. Burszta-Adamiak E., Dąbrowska J., Lejcuś K., **Marczak D.**, Misiewicz J. Śpitalniak M., Wróblewska K. *Koncepcje i kryteria doboru rozwiązań zrównoważonych systemów drenażu dla obszaru pasa drogowego*. XXIII Międzynarodowa Konferencja Naukowa – Enviro. Kraków, 2018

10. Dąbrowska J., Garlikowski D., Lejcuś K., **Marczak D.**, Misiewicz J., Pawłowski A., Śpitalniak M. *Możliwości zastosowania geokompozytów sorbujących wodę w inżynierii środowiska*, Ogólnopolska Konferencja Naukowo-Techniczna „Współczesne wyzwania gospodarki wodnej na obszarach wiejskich". Polanica Zdrój, 2018
11. **Marczak D.** *Zielone dachy jako systemy retencji wód opadowych*. XXIII Międzynarodowa Konferencja Studenckich Kół Naukowych i XXXV Sejmik SKN. Wrocław, 2018

Patenty

09.2023	rozpoczęcie procedury mającej na celu uzyskanie ochrony patentowej na biodegradowalną wersję geokompozytu sorbującego wodę

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3	Budownictwo wodne	2022/2023
4	Gospodarka bezodpadowa	2022/2023
5	Grafika inżynierska	2022/2023 2020/2021
6	Systemy sanitarne	2022/2023
7	Wprowadzenie do badań naukowych	2022/2023 2021/2022
8	Oczyszczanie i zagospodarowanie wód opadowych	2022/2023 2020/2021 2019/2020
9	Składowiska odpadów	2022/2023 2019/2020
10	Gospodarka odpadami	2021/2022
11	Mechanika gruntów i fundamentowanie	2020/2021
12	Sieci wodociągowe i kanalizacyjne	2019/2020
13	Technologia informacyjna	2019/2020

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Review

Characteristics of biodegradable textiles used in environmental engineering: A comprehensive review

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A B S T R A C T

Geotextiles have become a popular solution in environmental engineering. They may be manufactured from synthetic or biodegradable materials. The main functions of geotextiles are: separation, filtration, drainage, sealing, anti-erosion protection, and improving plant vegetation conditions. The synthetic ones are produced mainly from fossil fuels. One of the ways to reduce the consumption of energy from non-renewable sources and to limit environmental pollution is to replace petrochemical materials with natural products. Unfortunately, only 2% of the geosynthetics are produced from renewable resources. However, it is estimated that natural fibers and biopolymers might successfully replace synthetic materials even in 50% of all applications. A wide range of geotextiles produced from such natural fibers as jute, flax, coconut fiber, palm fiber, sisal, nettle, straw, cotton, and wool are currently available on the market but they are not widely used in environmental engineering. The paper presents the current state of knowledge and technological developments in their production and application. The study also points to the existing deficiencies and opportunities in the development of the manufacturing technology of natural fibers and biodegradable polymers.

Contents

1. Introduction . . . 2
   1.1. Pollution with synthetic textiles in environmental engineering . . . 2
   1.2. The potential of biotextiles in environmental engineering . . . 2
   1.3. The use of geotextiles . . . 2
2. Methodology . . . 3
   2.1. Selection of databases . . . 3
   2.2. Selection of searched terms . . . 3
   2.3. Bibliographic results . . . 3
3. Textiles made of natural fibers . . . 3
   3.1. Properties and classification . . . 3
   3.2. Plant fibers . . . 4
      3.2.1. Fibers obtained from fruit and seeds . . . 6
      3.2.2. Bast fibers . . . 7
   3.3. Animal fibers . . . 8
      3.3.1. Wool fibers . . . 9
4. Modification of natural fibers . . . 9
5. Biodegradable polymers . . . 10
6. Conclusion . . . 12
   Declaration of competing interest . . . 13
   Acknowledgements . . . 13

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References 13

1. Introduction

1.1. Pollution with synthetic textiles in environmental engineering

In recent years, geotextiles have become a popular solution that is successfully used in environmental engineering and the construction industry. Geotextiles are applied in engineering structures in form of fabrics, non-woven or knitted fabrics, mats or tapes. The optimum selection of geotextile materials is closely linked to the local hydrogeological conditions, the function that the textile will perform and the intended results (Lekha and Kavitha, 2006). The main functions of geotextiles include: separation, filtration, drainage, anti-erosion protection, sealing, protection of geotechnical systems as well as improving plant vegetation conditions (Broda et al., 2016; Hsieh et al., 2017; Ivanov and Chu, 2008; Lekha and Kavitha, 2006; Marques et al., 2014; Michael V. Harding et al., 2013). Geotextiles may be manufactured from synthetic or biodegradable materials. Synthetic fibers are characterized by high durability. They are usually not subject to biological degradation, they are also quite robust and easily available, so they are widely used (Sülar and Devrim, 2019). Such growing interest in this type of products leads to a continuous increase in the production of plastics, which consumes enormous amounts of fossil fuels. In the last 15 years, global production of plastics doubled, reaching approximately 299 million tons in 2013. In Europe, the use of such artificial materials is dominated to a large extent by packaging (38%), followed by construction and widely understood environmental engineering, which account for approx. 21% of the total use (Hahladakis et al., 2018). Plastics are manufactured from non-renewable resources, and their combustion causes greenhouse gas emission, which in turn contributes to climate change and environmental pollution. One of the ways to reduce the consumption of energy from non-renewable sources and to limit environmental pollution is to replace petrochemical plastics gradually with natural products. Thanks to that, the whole investment will meet the requirements of sustainable development (Andrady, 2017; Chauhan et al., 2008; Subaida et al., 2009; Väisänen et al., 2017).

1.2. The potential of biotextiles in environmental engineering

At the present moment, the demand for commonly applied geotextiles is soaring, which is proven by the fact that 1400 million square meters of these fabrics are used annually. Unfortunately, only 2% of this amount is produced from renewable resources. However, it is estimated that natural fibers and biopolymers might successfully replace synthetic materials even in 50% of all applications (Prambauer et al., 2019). A wide range of textiles produced from such natural fibers as jute, flax, coconut fiber, palm fiber, sisal, nettle, straw, cotton, and wool is currently available (Kumar and Das, 2018; Lekha, 2004; Rawal and Sayeed, 2013; Sarsby, 2007; Shanks et al., 2006; Sukudom et al., 2019; Yang et al., 2016). Although plant and animal fibers have been available for centuries, people failed to notice their potential to be used in form of geotextiles. This resulted mainly from the limited reliability and durability of these materials. The key to successful application of natural geotextiles is the determination of their intended functions, required properties and longevity already at the design stage, followed by the selection of the appropriate biodegradable material (Ku et al., 2011; Sgriccia et al., 2008). The concept of introducing natural materials of a specific degradation time requires first of all defining the period in which the material should perform the intended role. Materials used for manufacturing biotextiles should be selected so that the gradual deterioration of their properties is proportionate to the improvement of soil conditions (Mwasha, 2009a). Geotextiles made from natural materials installed in soil guarantee instant protection. Then, in the process of their gradual biodegradation, they supply organic matter and nutrients to plants, which improves their vegetation, and, first of all, they do not have an adverse impact on the environment (Broda et al., 2016; Sarasini and Fiore, 2018; Shavandi and Ali, 2019). As opposed to natural materials, plastics are considered as permanent pollutants. Some popular examples of practically non-biodegradable polymers are PET and PP. Only 0.1% of carbon in the PET polymer is transformed into CO_2 annually in the biodegradation process and even that takes place only in laboratory conditions (Hahladakis et al., 2018). The fact that the degradation of geotextile materials in the environment poses such serious problems should inspire us to consider other, generally available and environmentally friendly solutions. In this light, biodegradable geotextiles were considered as one of the best solutions, which complies with the principles of sustainable development and provides natural fertilization for plants at the same time (Hsieh et al., 2017; Lekha, 2004; Marques et al., 2014).

1.3. The use of geotextiles

Apart from using the geotextiles in order to stabilize slopes, they have numerous other applications in which these materials are used successfully, including (Sarsby, 2007; Subaida et al., 2009; Venkateswarlu et al., 2018):

- road construction, as elements reinforcing the surface of airports, car parks, and asphalt paving,
- reinforcement systems on embankments, railroad track beds, reinforcement of the banks of natural and artificial water reservoirs, or the abutments of bridges and overpasses,
- the construction of artificial water channels, reinforcement of high and steep earth walls to prevent them from sliding,
- the construction of landfills, drainage of paved areas, sports facilities and roads.

Depending on the intended location, local conditions, and the expected benefits, the selection of geotextiles should be based on the following properties (Arshad et al., 2014; Rawal et al., 2010): physical, mechanical, hydraulic and rheological properties. Improving our knowledge about the properties of natural materials may be the basis for their wider application and, in consequence, to introducing certain modifications if their potential is insufficient for the given conditions. Homogeneous, stable geotextile fibers, characterized by the desired biodegradation time, may be obtained by means of modifying natural fibers with use of physical and chemical methods, by combining different polymers and fibers and using biopolymers (Prambauer et al., 2019).

The aim of the paper is to review the available biodegradable textile materials used in environmental engineering. Thus, it presents information about the most commonly used natural fibers (flax, jute, hemp, kenaf, coconut, cotton, palm tree, sisal, bamboo and wool) and biopolymers (PLA, PHA, PCL, PHB, PBS, and CA). The authors considered the general characteristics of fibers, including their source of origin, classification, chemical composition, mechanical properties, and the potential biodegradation time in controlled and practical conditions. Additionally, the paper presents a review of the methods of mechanical and chemical modification of plant and animal fibers, including electric discharge (corona, cold plasma), fibrillation of fiber, ultrasonic treatment, alkaline modification, modification with silan, acetylation, benzoylation treatment and propionylation. The final sections contain conclusion and a description of trends, as well as key issues that should be solved to enable common application of biopolymers.

2. Methodology

The literature review was organized and conducted in the following stages:

- determination of the objective and scope of research work,
- data search and collection,
- analysis of the obtained data,
- reporting and qualitative elaboration of the results,
- formulating conclusions.

These stages were described in the following sections: introduction; textiles made with use of natural fibers; animal fibers; modification of natural fibers; biodegradable polymers; conclusions.

2.1. *Selection of databases*

The following literature databases were selected for review: Web of Science, Scopus, Science Direct, and Google Scholar. Selecting several databases enabled us to find over 1000 potentially interesting references. In order to obtain a manageable number of sources, the authors decided to focus mainly on peer-reviewed academic papers published in the English language in the years 2000–2019, that account for over 89% of the finally selected literature. Due to certain gaps, concerning mainly the properties of selected plant fibers, the authors decided to take into consideration 23 publications consisting of books or chapters thereof.

2.2. *Selection of searched terms*

Firstly, a general search based on keywords and their combinations was conducted with use of a year of publication filter (2000–2019). The key words for materials were: “jute”, “flax ”, “coconut fiber”, “palm fiber”, “sisal”, “nettle”, “straw”, “cotton”, and “wool”, as well as: “biotextile”, “biocomposite”, “plant fiber”, “animal fiber”, “bast fiber”, “leaf fiber”, “natural fibers”, “biochemical properties”, “sustainable geotechnics”, “fiber-reinforced soil”, “biodegradation of animal fibers”, “biodegradation of plant fibers”, “properties of natural textile materials”, “modification of natural fibers”; “biodegradable polymers”. These searches generated about 1000 results (including duplicates). Relevancy assessment was followed by quality evaluation. The materials found were divided according to authors and analyzed in terms of abstracts. In this way, about 250 articles were selected. At the subsequent stage, the articles were carefully read and analyzed. Numerous publications were excluded again, as they did not meet the requirements of the study or were considered irrelevant. As a result, 158 articles were selected. In order to ensure that no important topics in the selected literature had been omitted, we additionally searched the reference lists of other authors. In this way, 20 further papers were added to the review. We also added 23 publications consisting of books or chapters thereof. A total number of analyzed papers is 201.

2.3. *Bibliographic results*

The analyzed papers (201) were published in 100 journals and 23 books in the following fields: geotechnical engineering, engineering geology, mechanical engineering, materials science, mechanics of materials, ceramics and composites, polymers and plastics, organic chemistry, and materials chemistry. The keyword query included approximately 100 journals, of which 7 the most quoted were:

- Geotextiles and Geomembranes (14 articles, 7.11%),
- Composites Science and Technology (10 articles, 5.08%),
- Carbohydrate Polymers (7 articles, 3.55%),
- Composites Part A: Applied Science and Manufacturing (7 articles, 3.55%),
- Materials & Design (6 articles, 3.05%),
- Composites Part B: Engineering (5 articles, 2.54%),
- Materials (5 articles, 2.54%).

Although the oldest analyzed article originates from 2000, most of them were published in the last few years (Fig. 1.). The moving average from the last 5 years shows that the annual number of publications has been increasing, from approx. 3 papers in 2004 to approx. 15 in recent years.

Numerous publications among the analyzed literature presented information on more than one material in a single paper (Fig. 2). In order to provide a clear illustration of the information on the possibility to find data on specific materials, the selected publications were divided into 4 groups:

- plant fibers: coir, palm, sisal, jute, flax, kenaf, hemp, cotton, bamboo, wood, wheat, rice;
- animal fiber: wool;
- biopolymers;
- modification.

3. Textiles made of natural fibers

3.1. *Properties and classification*

The market offers a wide range of natural fibers, which are divided into three main groups, according to their origin: plant (cellulose) fibers, animal (protein) fibers, and mineral fibers (Fig. 3.) (Sathishkumar et al., 2014). Plant fibers may be obtained from various parts of the plants: seeds, stems, leaves, as well as fruit. Animal fibers are mainly obtained from the hair and silk (Akil et al., 2011; Faruk et al., 2012). Mineral fibers (asbestos) play a marginal role in environmental engineering, so their properties have not been analyzed in this review.

The mechanical, physical, and chemical properties of fiber are determined by the type of fiber and the processes that it undergoes from the moment of picking to the final product. Obtaining specific types of fibers requires picking them, repulping, cleaning, and drying. Although most natural fibers are characterized by a high cellulose content, while animal fibers contain large amounts of protein, their structure and properties may differ. These differences are reflected, among others, in the mechanical properties of the given material, and finally during the degradation process (Faruk et al., 2012; Staiger and Tucker, 2008). Regardless of their properties, specific fibers may be processed in order to obtain a wide range of products, including thread, rope, mats, textiles and nets. Others may be used as components of composite materials (Kozłowski, 2012).

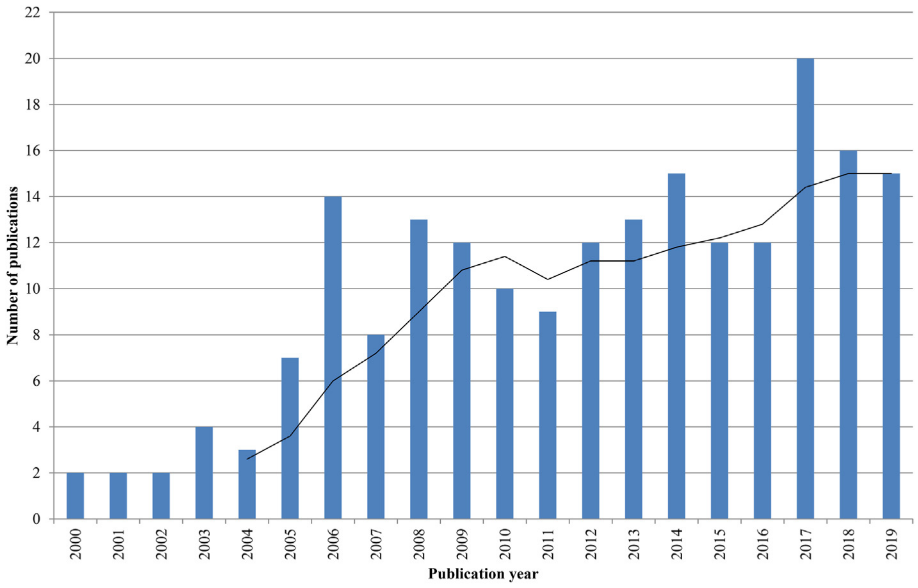

Fig. 1. Annual number of publications from 2000 to 2019 analyzed in this review (201 publications).

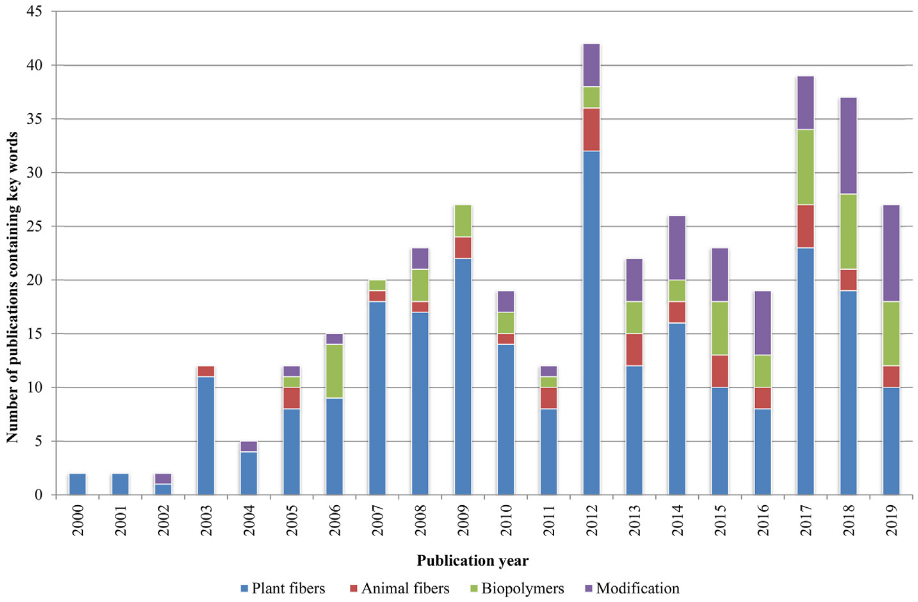

Fig. 2. The total number of publications from the years 2000–2019 was 201. One publications could appear several times in the calculations.

3.2. *Plant fibers*

Natural plant fibers have several advantages, such as their common availability, low manufacturing costs, renewability, and high quality. What is the most important is the fact that they are biodegradable, which makes them environmentally friendly (Rana et al., 2014; Sarikaya et al., 2019). The main component of plant fibers is cellulose, which ensures the appropriate mechanical resistance, stiffness of fibers, and influences the hygroscopic properties of materials (Zakikhani et al., 2014). Cellulose is subject to microbiological biodegradation as a result of enzymatic hydrolysis that consists in multi-stage hydrolysis of cellulose to glucose (Gutarowska and Michalski, 2012). Most plant fibers also contain hemicellulose, lignin, wax and pectin, which make the fibers more elastic (Akil et al., 2011; John and Thomas, 2008). Hemicellulose represents a type of heteropolysaccharides with a complex structure that contains glucose, xylose, mannose, galactose, arabinose and fucose in various proportions, depending on the source. Lignin is one of the main components — in wood it may account for approximately one third of the material's weight. It creates a protective layer that prevents the internal structure of fibers from degrading, it is not soluble in water and it is durable: it acts as a "glue" that connects cellulose and hemicellulose (Bordoloi et al., 2017b; Watkins et al., 2015). Moreover, lignin ensures stiffness and binds to hemicellulose and cellulose. It is believed that it prevents cellulose fibers from swelling in water (Gonzalez-Estrella et al., 2017). Fig. 4 shows a diagram of the structure of plant fibers.

The chemical composition of specific fibers cannot be neglected when selecting the appropriate materials for the given environment. Plant fibers have a good water absorption capacity, which,

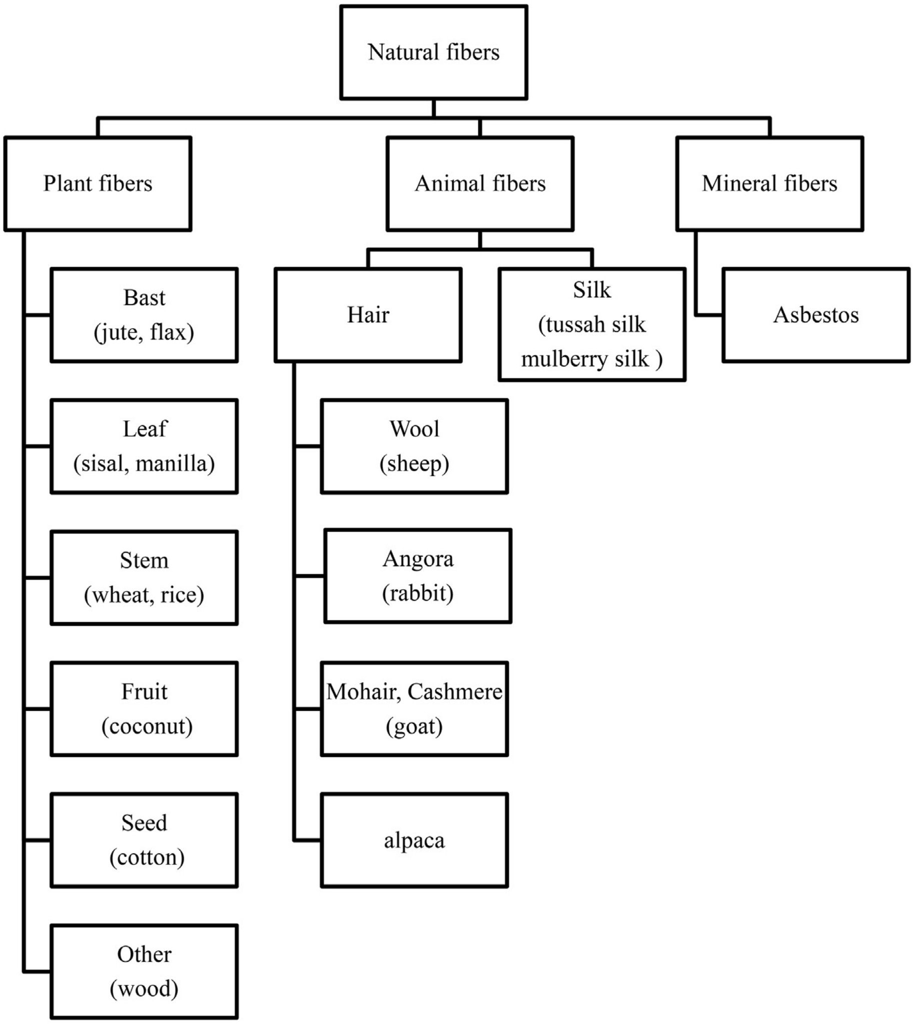

Fig. 3. Classification of natural fibers (Akil et al., 2011; Cassidy and Goswami, 2017; Faruk et al., 2012).

among others, contributes to the reduction of surface runoff during torrential rainfall and supports the vegetation of plants by gradually releasing moisture to soil during periods of drought. This property is considered to be one of the main advantages of natural fibers as opposed to synthetic ones, which are usually strongly hydrophobic (Prambauer et al., 2019). On the other hand, the main disadvantage of plant fibers is their chemical heterogeneity and their varied dimensions, which directly affects their mechanical properties (Bismarck et al., 2005). The diversity in individual properties of natural fibers results from numerous factors, such as the geographical location of the plantation, the chemical composition of oil substrate, the ripeness, size and part of the plant from

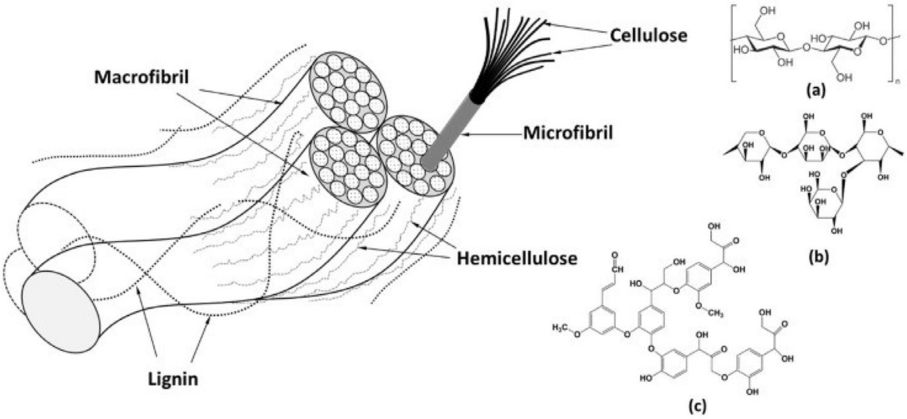

Fig. 4. Structure of plant fibers and the chemical composition of (a) Cellulose; (b) Hemicellulose; (c) Lignin. Data are from (Gowthaman et al., 2018).

which fibers are obtained. Fiber strength is also connected with the manner of picking crops, separating the fibers and storing them (Ramamoorthy et al., 2015). Table 1 presents the main chemical properties of selected fibers, which directly influence the scope of their application. These include: content of cellulose, hemicellulose, lignin and wax. Table 2 presents physical and mechanical parameters, including the length, width, strength, and biodegradation pace of the fibers. The following sections provide a detailed presentation of chemical properties of the fibers and their influence on their mechanical properties. The authors also reviewed the studies on biodegradation of the most commonly used materials of plant origin. The materials were selected based on their availability, possibilities of application, degree and pace of degradation.

3.2.1. Fibers obtained from fruit and seeds

One of the most commonly used fibers obtained from seeds is cotton (Yafa, 2006). The first documented application of plant fiber in construction took place in South Carolina in 1926. The Highway Department initiated a series of tests on the application of cotton geotextiles in order to reduce the damage to asphalt paving (Sarsby, 2007). Cotton fiber is also a valuable raw material in the textile industry. Its value results from several properties that may be maintained, provided that the crops are collected correctly and that the material is stored and then further processed in an appropriate way. One of the effects of proper use of cotton is its resistance to bacteria and fungi. The surface of cotton fiber is covered by a thin layer of wax, which provides a protective coating that guarantees chemical resistance (Kozłowski, 2012). Among all plant fibers, cotton has the highest cellulose content (85–96%), which ensures good hydrophilic properties. As a result of cotton degradation, valuable elements are released to the environment, which then serve as fertilizer for plants (Bax and Müssig, 2008; Ioelovich and Leykin, 2008). Hsieh (2007) pointed out that the chemical composition varies depending on the variety of cotton, the environment where it is cultivated and the degree of ripeness of fibers. It was noted that the cellulose content increases with the increasing degree of ripeness (Table 3.).

The composition of cotton fiber directly influences the degree and pace of its biodegradation. Li et al. (2010a,b) analyzed the degradation of cotton in compost and laboratory conditions. Composted samples of cotton fiber lost approximately 55% of their initial weight after 90 days, while in laboratory conditions the pace of biodegradation was much slower. On the other hand, research conducted by Arshad et al. (2014) demonstrated that cotton decomposed faster when it was exposed to direct contact with soil. In such conditions, the textile was nearly completely decomposed already after 3 weeks of the experiment. The biodegradation process slowed down significantly when the fibers were put inside hydrophobic bags. In these conditions, the weight loss was approx 37–45% after three months. Interestingly, cotton stored in appropriate conditions, where it is not exposed to the microorganisms that exist, for example, in soil, shows only a slight deterioration of its original properties, even after 50 years (Rana et al., 2014). This doubtlessly indicates that this fiber is strongly susceptible to the activity of microorganisms, for which it is a valuable source of nutrients.

Another popular fiber, which is obtained from the husk surrounding the fruit, is coconut fiber. These fibers are commonly used to manufacture ropes, threads, carpets, mattresses and geotextiles (Ramamoorthy et al., 2015; Vishnudas et al., 2006). Coconut fibers are usually 5–350 mm long and their main components are cellulose (36–43%), and hemicellulose (0.15–0.25%). What is characteristic, is the fact that coconut has the highest lignin content (41–46%) among all natural fibers (Lekha, 2004; Ramamoorthy et al., 2015; Sivakumar Babu and Vasudevan, 2008). In spite of lower cellulose content, the structure of coconut fibers is very dense, which makes them more durable in comparison to other natural fibers (Lekha, 2004). On the other hand, high lignin content makes them stiffer, more resistant to elongation and lowers water absorption capacity, which significantly prolongs their resistance to microbiological degradation (Sumi et al., 2018; Viswanathan et al., 2000). Moreover, textiles produced from coconut fiber are characterized by good resistance to high temperatures, and they positively influence the mechanical and chemical properties of soil (Reis, 2006; Tomczak et al., 2007). Coconut fiber is one of the few fibers that are resistant to the influence of salty water, which makes it an attractive product for maritime engineering (Müssig et al., 2010; Vishnudas et al., 2012). Nevertheless, the main disadvantages of this material include relatively low tensile strength and large thickness of bunches in comparison to such other fibers as flax and hemp (Ramamoorthy et al., 2015). Due to its rough texture with numerous small pores on the surface, the fiber gradually absorbs moisture. This property increases with the progressing degradation, whose pace depends directly on the pH of soil, the

Table 1
Biochemical composition of selected plant fibers in reference to their origin.

Fiber	Source	Cellulose [%]	Hemicellulose [%]	Lignin [%]	Wax [%]	Reference
Flax	Stem	62.0–72.0	18.6–20.6	2.0–10.0	1.7	(Bordoloi et al., 2017a; Faruk et al., 2012; Ramamoorthy et al., 2015; Satyanarayana et al., 2009)
Jute	Stem	56.0–71.5	13.6–35.0	11.0–15.9	0.5	(Akil et al., 2009; Bordoloi et al., 2017b; Faruk et al., 2012; Gowthaman et al., 2018; Ramamoorthy et al., 2015)
Hemp	Stem	64.0–78.3	16.0–22.4	2.9–5.7	0.8	(Dhakal et al., 2007; Laborel-Préneron et al., 2016; Ramamoorthy et al., 2015)
Kenaf	Stem	44.0–72.0	3.0–21.0	9.0–19.0	–	(Faruk et al., 2012; Kiruthika, 2017; Laborel-Préneron et al., 2016; Millogo et al., 2015)
Coconut	Fruit	32.0–43.8	0.25–14.7	38.3–46.0	–	(Abiola, 2017; Bordoloi et al., 2017b; Laborel-Préneron et al., 2016; Satyanarayana et al., 2009)
Cotton	Seeds	82.7–95.0	5.7	0.0	0.6–5.0	(Liu et al., 2019; Ramamoorthy et al., 2015)
Palm tree	Fruit	32.0–65.0	17.1–33.5	13.2–28.9	0.6	(Kaddami et al., 2006; Ramamoorthy et al., 2015; Shinoj et al., 2011)
Sisal	Leaves	43.0–88.0	10.0–14.2	5.0–14.0	2.0	(Abiola, 2017; Badrinath and Senthilvelan, 2014; Gupta and Srivastava, 2014; Thakur, 2013a)
Bamboo	Grass	26.0–73.8	12.5–30.0	10.2–31.0	–	(Abiola, 2017; Ramamoorthy et al., 2015; Thakur, 2013a)
Wood	Stem, core	45.0–50.0	23.0–36.0	22.4–27.0	–	(Ji et al., 2018; Thakur, 2013a)
Wheat	Straw	35.0–45.0	15.0–31.0	12.0–20.4	–	(Abiola, 2017; John and Anandjiwala, 2008; Ramamoorthy et al., 2015; Watkins et al., 2015)
Rice	Straw	28.0–70.0	33.0	8.0–19.0	8.0–38.0	(Abiola, 2017; Müssig et al., 2010; Ramamoorthy et al., 2015)

Table 2
Physical and mechanical properties of selected plant fibers.

Fiber	Mean length [mm]	Mean width [µm]	Density [kg/m^3]	Tensile strength [MPa]	Elongation at break [%]	Young's modulus [GPa]	Degradation time [months]	Reference
Flax	33.0	19.0	1380	343–1035	1.2–3	27.6	3	(Abiola, 2017; Biswas et al., 2015; Shanks et al., 2006)
Jute	2.0	20.0–66.0	1230	187–773	1.5–3.1	13.0–31.0	6–18	(Abiola, 2017; Müssig et al., 2010; Saha et al., 2012)
Hemp	25.0	25.0	1350	580–1110	1.2–4.5	30.0–70.0	3–8	(Abiola, 2017; Ochi, 2011; Ramamoorthy et al., 2015)
Kenaf	2.5–2.6	40.0	1200	295–930	1.6–6.9	53.0	6–12	(Abiola, 2017; Hojo et al., 2014; Liao et al., 2014; Nishino et al., 2003; Ramamoorthy et al., 2015)
Coconut	0.7	20.0	1200	175	30.0	4.0–6.0	6–36	(Lekha, 2004; Müssig et al., 2010; Mwasha, 2009b; Sumi et al., 2018)
Cotton	20–64	11.5–20.0	1550–1600	300–700	7.0–8.0	5.0–13.0	1–6	(Abiola, 2017; L. Li et al., 2010b; Satyanarayana et al., 2009)
Palm tree	6.0	15.0–50.0	700–1550	50–400	4.0–18.0	3.2–9.0	–	(Abiola, 2017; Ramamoorthy et al., 2015; Shinoj et al., 2011)
Sisal	201.1	13.2–23.7	1300–1500	468–885	3.0–7.0	9.4–22.0	12	(Methacanon et al., 2010; Prambauer et al., 2019; Ramamoorthy et al., 2015)
Bamboo	2.7	14.0	800–1400	290–1000	2.0	11.0–30.0	12–36	(Abiola, 2017; Biswas et al., 2015; Ramamoorthy et al., 2015; Satyanarayana et al., 2009)
Wood	1.0–3.5	25.0–50.0	440	1000	–	40.0	6–12	(Laborel-Préneron et al., 2016; Müssig et al., 2010; Netravali and Chabba, 2003)
Wheat	–	–	1600	273	22.7	4.8–6.6	<6	(Abiola, 2017; Müssig et al., 2010)
Rice	0.7–3.5	5.0–14.0	1650	449	2.2	1.2–1.3	<6	(Abiola, 2017; Müssig et al., 2010; Tavakoli et al., 2010)

Table 3
Composition of cotton fiber depending on the degree of ripeness (Ugbolue, 2005).

Components	Ripe cotton fiber [%]	Unripe cotton fiber [%]
Cellulose	96.41	92.44
Minerals	0.79	1.32
Wax	0.45	1.14
Protein	1.00	2.00

temperature and the presence of microorganisms (Vishnudas et al., 2012). Research on the pace of biodegradation of coconut fiber was conducted, among others, in the mountainous regions of the UK. The installed geotextiles performed their functions correctly for at least three years and they proved to be an effective tool protecting slopes against erosion (Ghosh et al., 2009). The influence of local conditions in the south-east of Brazil on the degradation of coconut fiber was analyzed by Marques et al. The analyses of tensile strength of the fiber demonstrated that the material retained approx. 23% of this property after 12 months of exploitation (Marques et al., 2014). The degradation pace of coconut geotextile was high during periods of intense rainfall, but along with degradation, organic matter and nutrients were released to the soil substrate, improving its fertility (Marques et al., 2014; Rickson, 2006). Similar results were obtained by Vishnudas et al. (2005) who analyzed the usability of geotextile made from coconut fiber for the protection of watersheds in local conditions in India. In this study, the coconut fiber lost approximately 80% of its original tensile strength after 9 months of exploitation. However, this period was sufficient for the plants to stabilize the slopes.

The analysis of the characteristics and possibilities of application of fibers obtained from seeds and fruit revealed that coconut fiber had by far the best properties. This fiber is usually a by-product in obtaining coconuts for the food and oil industry, which would otherwise require disposal. As opposed to other plant fibers, it is characterised by higher resistance to biodegradation. Various sectors of industry are currently interested in improving the technology of spinning coconut fiber (Chattopadhyay and Chakravarty, 2009; Prambauer et al., 2019). An important indicator of the potential of this fiber are geotextile products available on the market, which are successfully applied not only in environmental engineering, but also in gardening or agriculture (Ramírez-Arias et al., 2014). In a further perspective, the main focus should be on activities aimed at the stabilisation of the fiber's mechanical parameters and adjusting the degree of biodegradation to the time in which it is expected to perform specific functions in real conditions. This problem may be solved by a more detailed analysis of the potential of such modifications as plasma treatment, reinforcement with epoxy resin, and alkaline modification (De Oliveira et al., 2017; Gowthaman et al., 2018; Kumar Dutta et al., 2012).

3.2.2. *Bast fibers*

Bast fibers are defined as fibers obtained from the external cell layers of such fiber crops, as flax, jute or hemp (Crônier et al., 2005; Summerscales et al., 2010). These are usually annual crops, whose vegetation period lasts three to four months. Bark or skin protects the plant from evaporation and sudden temperature changes, and provides partial reinforcement of the stem (Zimniewska et al., 2011).The fiber is located directly under the skin and it accounts for approximately one third of the weight. The core that is located in the central part of the stem resembles wood and it has several applications — it may be used to manufacture litter for animals, mats, or as fuel. During the manufacturing process, bast fibers undergo initial mechanical or chemical processing in order to obtain the required quality, which in turn determines their final use (Abiola, 2017; Müssig et al., 2010; Summerscales et al., 2010).

Such fibers have several advantages, of which the most important are (Madsen and Gamstedt, 2013; Ramamoorthy et al., 2015):

- they are obtained from annual crops, which results in high production performance and large supply of materials;
- high cellulose content, the degree of cellulose crystallization, low angle of microfibrils and small gauge (0–5%) guarantee good mechanical properties of the fibers;
- relatively long fibers (5–50 mm) enable to control their orientation and placement;
- well patented technology of processing these types of fibers enables the production of yarn, fabrics and textiles in an intact condition and high quality of the products.

One of the oldest and best known representatives of bast fibers is flax (Kicińska-Jakubowska et al., 2012). Two main groups of flax plants are distinguished: those cultivated for fiber and those from which oil is produced. Plants from the first group reach the height of 80–120 cm, while the oil varieties are shorter: 60–80 cm, and thicker. Fiber varieties of flax are used not only in the textile industry, but also in the production of composites and paper (Zimniewska et al., 2011). Flax fibers contain approximately 70% cellulose, 18% hemicellulose, 5–10% lignin, and wax. The presence of lignin causes the roughness of plant cells, which in turn leads to loss of smoothness, elasticity, and increases the brittleness of the fiber (Kicińska-Jakubowska et al., 2012; Pekhtasheva et al., 2012; Zimniewska et al., 2011). Due to low elasticity, the fibers do not return to their original shape after crumpling. Flax fibers have an outstanding tensile strength. What is characteristic, is that the strength of wet fibers is higher, which makes them an attractive material for manufacturing mats, nets or geotextiles. Flax fiber is strongly hygroscopic, but it is a weak thermal insulator (Abiola, 2017; Müssig et al., 2010). After the end of exploitation, flax geotextiles undergo complete biodegradation, supporting the vegetation of plants. Alimuzzaman et al. (2014), in their research analyzed the degree and pace of biodegradation of flax and of composites from polylactide reinforced with flax (PLA).It was noted that with the increase in the content of flax fiber, the mechanical properties of biocomposites deteriorated, which accelerated the biodegradation process. Flax fibers and their biocomposites degraded rapidly during the first 40 days, losing weight equivalent to the approximate content of flax fiber. In the subsequent 80 days, further gradual decrease in weight was noted. Finally, a sample made from 100% flax lost 90% of its initial weight after 120 days of exploitation in soil. The main cause of biodegradation was the presence of microorganisms, whose activity was closely linked to the presence of water in soil.

Another very popular example of fiber crops is jute, which is relatively cheap and widely used in the industry (Mahesh et al., 2019; Sanyal, 2017). It is commonly cultivated in Asia, as well as in Brazil (Hejazi et al., 2012; Satyanarayana et al., 2007). Depending on the variety, it may grow as high as 2.5–4.5 m, with stem width of approx. 25 mm (Gowthaman et al., 2018).Jute fiber consists of 56–71% cellulose, 29–35% hemicellulose and 11–14% lignin (Gowthaman et al., 2018; Zhang et al., 2019).The texture of the fiber surface is highly irregular, with numerous peaks and valleys of various sizes, located at various distances from each other, which results in a rough texture. Such properties may potentially foster adhesion and cause friction drag on the soil-fiber border. These properties of jute fabric make it a consistent matrix of the desired resistance and sufficient plasticity (Zhang et al., 2019). It was found that jute fiber is effective in improving the geotechnical properties of soil. As a result, the fiber is widely used in consolidation, drainage, soil filtration, road construction, stabilisation and protection of slopes, and erosion control (Bordoloi et al., 2017a; Chattopadhyay and Chakravarty, 2009; Datta, 2007; Ghosh et al., 2017; Gowthaman et al., 2018). Geotextiles based on jute fibers have several additional advantages connected with specific applications. For example, the swelling and water absorption help reduce surface runoff and improve the filtration properties of soil to increase stability and minimize erosion. Additionally, they prevent extreme changes in soil moisture and temperature. geotextile made from jute may absorb even up to 270% water in comparison to its dry weight, retaining moisture during periods of intense rainfall and releasing it gradually during periods of water deficit (Saha et al., 2012). The hydrophilic properties of jute fibers affect the biodegradation pace directly. Saha et al. (2012) in their studies compared the durability of unprocessed jute textiles to that of jute geotextiles subjected to chemical processing. As far as chemical degradation was concerned, unprocessed fibers showed low resistance to the effects of salt water and maintained only 17% of their initial tensile strength after 120 days of soaking in 3% NaCl solution. The degree and pace of biodegradation was assessed by placing samples of geotextile in specially prepared substrate. The experiment, planned for 200 days, demonstrated that the process of degradation of unprocessed sample of jute was quite dynamic and that the textile was completely biodegraded as soon as 90 days of exposure. The analysis and comparison of the obtained results demonstrated that the environment, in which the textiles were subject to biodegradation, was too harsh compared to typical field conditions. Ultimately, the obtained result was modified with use of a specifically selected coefficient, and the time of biodegradation was estimated to be approx. 380 days.

Jute-based geotextiles are the most deeply analyzed and commonly appreciated among bast fibers. Its wide availability, high production capacity and low processing costs are essential in promoting this fiber (Kiruthika, 2017; Mahesh et al., 2019). From the engineering point of view, another, equally valuable property should be its high resistance and elasticity (Prambauer et al., 2019). The high potential of jute fibers is best proven by the large scale of production of jute geotextiles. However, limiting its vulnerability to microbiological decomposure should be a barrier, and, at the same time, a challenge for scientists. Modifying the fiber, e.g. by trans-esterification, reinforcement with epoxy resin, alkaline modification might provide a chance to eliminate this factor (Pujari et al., 2017; Ray et al., 2002; Saha et al., 2012). High effectiveness of these treatments are proven by research projects discussed in the subsequent sections, which should be continued on a wide scale in practical conditions and then gradually introduced to commercial solutions.

3.3. *Animal fibers*

Fibres from wool, angora, mohair, cashmere and alpaca have the most significant economic value in the textile market today (Shavandi et al., 2017; Shavandi and Ali, 2019). Textiles made from silk or high-quality wool are used in such sophisticated applications as manufacturing biomedical materials and clothing (Ellison, 2013; Ramamoorthy et al., 2015). Lower quality materials produced from wool are successfully used in anti-erosion protection of slopes, or reinforcing earthwork structures. They are also applied in construction as insulation materials or in agriculture as fibrous substrates that are a rich source of nutrients for plants (Bosia et al., 2015; Broda et al., 2017b; Zach et al., 2012; Zoccola et al., 2015).

Animal fibers are made from protein. The protein of wool is keratin, whereas of silk is fibroin. The major difference being that keratin fiber proteins are highly cross-linked by disulphide bonds, whereas the secreted silk fibroin fibers tend to have no cross-links and a more limited array of less complex amino acids. Basic elements in protein molecule is carbon, hydrogen, oxygen, and nitrogen (Sabir, 2018; Tridico, 2009). All mammalian hairs grow from follicles embedded in the skin, in contrast to the silks which are extruded from silk moth larvae. General properties of fibers may be determined based on the sequence and type of amino acids that create polypeptide chains. This difference affords each animal fibre type different and unique properties. Most mammal fibers consist of three layers: the external cuticle, the cortex and the core. The overlapping cuticle cells create a protective layer around the fiber. The cortex accounts for the major part of the weight and determines the mechanical properties of fibers. Due to high protein content, animal fibers are sensitive to high temperatures. The lowest resistance to temperature is found in wool, which becomes brown and degrades if exposed to a temperature of approx. 100 °C for a longer period of time. Silk, which loses its properties in the temperature of approx. 140 °C, is slightly more resistant (Bhattacharyya et al., 2015; Kozłowski, 2012; Ramamoorthy et al., 2015). Nevertheless, these natural proteins have several positive properties, such as biodegradability, biocompatibility and the ability to reduce flammability. However, they are first of all byproducts of agriculture, which makes them commonly available and very cheap (Shavandi and Ali, 2019).

3.3.1. Wool fibers

The fiber of wool is a bioproduct of great potential, which has become popular only recently and started to be promoted as an alternative material used in environmental engineering (Corscadden et al., 2014; Johnson et al., 2003). Wool has numerous physical properties that make is such an attractive resource. They include high strength, appropriate resistance to humidity, good thermal properties, natural ability to regulate temperature, and resistance to fire (Corscadden et al., 2014; Galán-Marín et al., 2010; Ye et al., 2006).

Wool fiber belongs to the group of protein fibers that have very complex structure. A single fiber contains approximately 82% keratin proteins of a high concentration of cysteine and 17% uncontaminated protein with relatively low cysteine content. Additionally, it contains approx. 1% weight of non-protein material, mainly wax lipids and polysaccharides (Broda, 2019; Rippon, 2013).

The length of the fiber is very varied and it falls into the range of 35–350 mm, while its thickness may vary from 16 to 36 μm. The internal structure of the fiber is characterized by heterogeneous shape, chemical content and properties. The differentiation of these basic parameters depends mainly on the breed of the animal and the location of the hair in the fleece. The main components of the fiber are: the cuticle — thin external layer, the cortex – a layer that fills practically the whole capacity of the fiber, the core – the central part that exists only in core hairs (Broda et al., 2017b; Rippon, 2013). The specificity of the structure of individual layers is reflected in their physical and chemical properties. In terms of these properties, the cuticle constitutes a hydrophobic coating with a high degree of elasticity, low value of surface friction coefficient and high chemical resistance. One of the characteristic properties of wool is its high resistance to acids. The fiber degrades only after exposure to strongly concentrated acids at high temperature. Similar properties were noted in contact with organic solvents. However, it was found that wool is relatively sensitive to alkaline compounds (Grishanov, 2011; Johnson et al., 2003). Tables 4 and 5 present selected chemical and physical properties of wool fibers.

The degradation of keratin substrates is caused by mechanical and biochemical processes initiated by specialized groups of bacteria and fungi (Błyskal, 2009). The accumulation of keratinophilic fungi in the natural environment is not homogeneous and it depends to the main extent on the pH of the soil. The presence of sulphur has vital influence on the properties of wool. Higher sulphur content in soil improves the resistance of wool to chemical agents, as well as its durability and elasticity of fibers, thus improving its physical and mechanical properties (Pekhtasheva et al., 2012). The biodegradation of keratin materials leads to the mineralization and biotransformation of nitrogen and sulphur into forms easily accessible for plants (Hustvedt et al., 2016; Korniłłowicz-Kowalska and Bohacz, 2011; Queiroga et al., 2012). As a result, wool undergoes gradual biodegradation, losing its mechanical properties in the process (Broda et al., 2018). Zheljazkov et al. (2005, 2009) demonstrated that in composting conditions, the decomposition of wool takes a relatively long time and that wool acts like a slow-release fertilizer that releases C, N, P, K, and S to soil. Wool used in soil has good hygroscopic properties: it retains large amounts of water during intense rainfall and then releases it gradually during periods of water deficit. Addition of 20–120 g of wool waste to pots with basil was sufficient to increase the crops 1.6–5 times in comparison to the control group. The biodegradation of wool in compost depended on the composition of compost and lasted 4–12 weeks. The nutrients originating from the decomposition of wool were present after 250 days of the experiment. In general, wool-based compost was assessed as a material that improves soil quality, among others by improving its aeration and permeability. It was also considered as an efficient biological means to reduce the number of pathogens and plant diseases.

Broda et al. (2017a) analyzed the degree and pace of biodegradation of meandrically arranged geotextile ropes made from wool and designed to protect slopes against erosion. The conducted research demonstrated that the ropes had excellent hygroscopic properties — they absorbed even up to 270% of water, which was later gradually released to the soil. After six months of exploitation, no visible signs of damage to the segments were noticed. The analysis of the mechanical properties of fibers revealed changes in the strength of geotextile. Depending on the location of ropes, the observed decrease in tensile strength ranged from 25 to 50%. Ultimately, the authors concluded that wool fibers maintain their protective potential for at least one vegetation season. This is sufficient time for the plants that are typically used to protect slopes to germinate, root, and grow.

Nowadays, manufacturing wool textiles has a high potential, especially as far as low quality wool is concerned, as it is currently treated as a troublesome by-product of breeding sheep. These fibers are characterised by sufficiently good mechanical properties and low obtaining costs. Moreover, they decompose into elements that do not pose a risk to the environment and may even be used as plant fertilizer. In spite of its numerous advantages, literature does not provide information about the biodegradation of currently used woolen geotextiles in practical conditions. These geotextiles have a high potential, especially in short-term solutions, where ensuring proper vegetation conditions is of key importance, e.g. in erosion control or land reclamation. As far as long-term solutions are concerned, it is necessary to obtain more in-depth knowledge about the potential modifications of these fibers or mixing them with other biopolymers. This topic has not been sufficiently analyzed yet, which is reflected by a low number of publications on the topic. This issue still requires a lot of further research and technological works.

4. Modification of natural fibers

In recent years, a series of studies has been conducted with the aim to replace synthetic fibers with fibers of natural origin. Although they have several advantages presented above, natural fibers are also characterized by some properties, which are undesirable in certain conditions, such as high water absorption, intensive swelling, gradual biodegradation and the loss of desirable mechanical properties. The possibilities to modify the surface of natural fibers with use of different techniques in order to minimize their disadvantages and to use these materials successfully in various environmental applications have a great potential (Cruz and Fangueiro, 2016). Natural fibers can be modified with use of physical or chemical methods (Tables 6 and 7). The physical

Table 4
Biochemical composition of wool.

Fiber	Source of origin	Carbon [%]	Nitrogen [%]	Oxygen [%]	Sulphur [%]	Reference
wool	wool	50	15–21	21–24	2–5	Pekhtasheva et al. (2012)

Table 5
Physical and mechanical properties of wool.

Fiber	Mean length [mm]	Mean width [mm]	Density [kg/m^3]	Tensile strength [MPa]	Elongation at break [%]	Degradation time [months]	Reference
wool	35–350	16–36	25–40	180–240	24–58	4–9	(Broda et al., 2016; Del Rey et al., 2017; Müssig et al., 2010)

methods include electric discharge (corona, cold plasma), fibrillation of the surface and ultrasonic treatment. Physical processing modifies the structural and superficial properties of the fiber and thus influences the mechanical properties of the textile. It is also used for the initial preparation of fiber for chemical processing. On the other hand, chemical methods reduce the decomposition of fibers caused by moisture, improving the fiber's adhesion and, as a result, the resistance of composites to moisture. The reduced pace of water absorption is different and it depends on the type of chemical processing (Azwa et al., 2013; Cruz and Fangueiro, 2016; Varghese and Mittal, 2018). The surface of cellulose fiber is rich in hydroxyl groups, which requires the use of specific reactions that are connected with such groups. Chemical methods may activate hydroxyl groups, which results in a significant improvement of the mechanical properties of fiber and reduces the pace of biodegradation of the materials. The most commonly used chemical modification methods include: acetylation, benzoylation and silanization (Li et al., 2007). Modified natural fibers have a significant advantage over synthetic materials due to their environmentally friendly nature and prolonged durability. Sumi et al. (2018) modified the surface of coconut fiber with use of a natural liquid obtained from cashew nut husks. It was noted that superficially modified geotextiles were more resistant to adverse chemical, physical and biological conditions than unprocessed textiles. Modified geotextiles that were used in the same field conditions as unmodified ones, maintained 70–80% of the initial tensile strength after 12 months, while unprocessed geotextiles lost nearly 90% of tensile strength after only four months.

The materials formed by the combination of inorganic materials and organic are attractive for the purpose of creating high-performance and high-functional polymeric biomaterials. Hybrid compositions are characterized by new unique properties that can be defined before the synthesis process of this type of materials. This available and inexpensive method of obtaining hybrid organic-inorganic composite materials is very good in the handling of cellulose fibers. This approach of biobased-hybrid materials represents an excellent way to produce high-performance materials with high content of inorganic nanoparticles for a wide variety of applications like energy efficient building material (Vasquez-Zacarias et al., 2018).

5. Biodegradable polymers

Growing problems with the environment and the attempts to reduce the amount of plastic waste resulted in an increasing diversity of biodegradable polymers in recent years (Prambauer et al., 2019; Sanjay et al., 2018). These polymers may be manufactured from petrochemical products, e.g. poly (ε-caprolactan) (PCL), as well as from such plant-based raw materials as starch, cellulose, e.g. polyhydroxyalkanoates (PHA), polylactide (PLA) in the process of chemical synthesis or direct biosynthesis (Prambauer et al., 2019). Tables 8 and 9 present the selected mechanical properties, main characteristics and the time of biodegradation of available biopolymers that might be successfully used in various types of environmental applications. The term biodegradable polymers or plastics refers to polymer materials that may be decomposed to carbon dioxide, methane, water, inorganic compounds or biomass. The durability and degradation pace of biopolymers depends on environmental impacts in the same way as it is in the case of geotextiles made from natural fibers. The dominant biodegradation mechanism is the enzymatic activity of microorganisms, which may be measured with standardized tests in a specific time and conditions (Song et al., 2009). As the main medium where polymer waste is decomposed is the soil, the changes in these polymers and their influence on this specific environment require more detailed discussion. Soil is characterized by varied biodiversity, which enables more efficient biodegradation of polymers than such media as water or air (Emadian et al., 2017). The time and degree of degradation of bioplastics may vary depending on substrate properties. A good example is provided in the research by Boyandin et al. (2013) on the biodegradation of PHA foil in local Vietnamese conditions. During 12 months of the experiment, over 98% of PHA foil was degraded in the Hoa Lac region in Vietnam, while in the soil environment of Dam Bai, also in Vietnam, the same material lost only 47% of its initial weight. The temperature, air humidity and soil moisture content in both test sites were similar for the whole duration of the project, and the significant differences in the progress of biodegradation of PHA foil in the Dam Bai region could

Table 6
Mechanical methods of fiber modification.

Fiber	Recommended treatment	Modification results	Reference
Cellulose fibers	Electric discharge (corona, cold plasma)	• increased adhesiveness and compatibility between fibers, • improved resistance parameters of textiles, • increased tensile strength, • reduced susceptibility to breakage, • increased roughness of textile.	(Thakur, 2013b, 2013a)
Cellulose fibers	Fibrillation of fiber	• improved elasticity, • increased share of microfibers that create a homogeneous, • improved mechanical properties of textiles, • creating additional hydrogen bonds between fibers and small particles	(Kangas et al., 2014; Li et al., 2019; Schenker et al., 2019)
Wool, cotton	Ultrasonic treatment	• cleaning the fiber surface from fat, wax and other contaminants, • improved effectiveness of chemical methods, • a combination of ultrasounds and enzymes may provide an alternative "green chemistry" solution for numerous industrial processes related to chemical processing of textiles.	(Easson et al., 2018; Kadam et al., 2013)

Table 7
Chemical methods of fiber modification.

Fiber	Recommended treatment	Modification results	Reference
Sisal, jute Flax Bamboo Palm fiber	Alkaline modification	• direct influence on the degree of polymerization, the extraction of lignin and hemicellulose compounds, • increased content of cellulose exposed on the fiber surface, • removal of natural and artificial contaminants that results in creating a rough surface with improved mechanical properties, • increased thermal resistance of the fiber, • improved tensile strength, • higher crosslink density and improved adhesion.	(Agrawal et al., 2000; Bachtiar et al., 2008; Gowthaman et al., 2018; Jacob et al., 2004; Joseph et al., 2019; Li et al., 2007; Suresh Kumar et al., 2014; Wang et al., 2018)
Kenaf, Flax Palm fiber	Modification with silan	• reduced swelling of fiber, • improved tensile strength, • improved thermal stability.	(Agrawal et al., 2000; Asim et al., 2016)
Sisal, Flax Hemp, Wood	Acetylation	• reduced moisture absorption, • improved dimensional stability of composites, • improved mechanical properties, • higher resistance to microbiological decomposition.	(Li et al., 2007; Rong et al., 2001; Rowell, 2004)
Wood, Flax, Coir jute Sisal,	Reinforcement with epoxy resin and nanoclay	• improved tensile strength, ductility and elasticity of textiles, • improved resistance to moisture and biodegradation, • improved thermal stability.	(Feng and Guo, 2016; Mittal et al., 2016; Mohan and Kanny, 2011; Van de Weyenberg et al., 2003)
Sisal, Flax Hemp, Wood	Propionylation	• reduced moisture absorption, • minimized bacterial colonization of the fiber surface, • reduced degree and pace of biodegradation.	(Kittikorn et al., 2018; Tserki et al., 2005)
Sisal,	Benzoylation Treatment	• improved mechanical properties, • reduced moisture absorption, • improved thermal stability.	(Li et al., 2007; Manikandan Nair et al., 2001)
Palm fiber jute Sisal, Cotton	Treatment with polyacrylic and acrylonitrile	• improved tensile strength, • increased inter-phase adhesion, • reduced water absorption.	(Kaur et al., 2013; Li et al., 2007; Xu et al., 2002)
Cotton, Hemp, Flax	Treatment with liquid ammonia	• smoothening fiber surface and improved gloss, • improved tensile strength, • improved dimensional stability,	(J. Li et al., 2010; Sun et al., 2016)

Table 8
Physical and mechanical properties of selected biopolymers.

Biopolymer	Density [g/cm^3]	Tensile strength [MPa]	Modulus of elasticity [GPa]	Reference
Polylactide (PLA)	1.24–1.34	41–70	2.6–7.8	(Aliotta et al., 2019; Prambauer et al., 2019; Raquez et al., 2013)
Polyhydroxyalkanoates (PHA)	1.17–1.39	18–35	0.5–3.2	Prambauer et al. (2019)
Poly (ε-caprolactan) (PCL)	1.05–1.15	15–55	0.4–0.8	Prambauer et al. (2019)
Thermoplastic starch blends	1.10–1.40	10–56	0.1–3.6	Prambauer et al. (2019)
Poly(hydroxylbutyrate) PHB	1.22–1.25	40	3.5	(Al et al., 2018; Altaee et al., 2016; Javadi et al., 2010)
Poly(butylenesuccinate) PBS	1.25	34–44.8	0.6–0.7	(Hemsri et al., 2015; Rudnik, 2019; Su et al., 2019)
Cellulose acetate CA	1.30	25–82	1.0–5.0	Prambauer et al. (2019)

have resulted from relatively low pH of 5.48, which probably led to deteriorated microbiological activity (Boyandin et al., 2013; Emadian et al., 2017).

The best known, most advanced technologically and most commonly used completely biodegradable polymer is PLA. Ohkita and Lee (2006) evaluated the degree and pace of biodegradation of composites from polylactic acid and corn starch. It was noted that the pace of degradation increased with the increase in CS content. This resulted from the fact that corn starch is highly susceptible to the activity of microorganisms that exist in soil. No biodegradation of PLA sheets occurred in soil for 6 weeks — the material remained intact, without any changes to its original shape. The analysis of this example leads to the conclusion that the additives used directly influence the pace of biodegradation, so the course of this process may be regulated effectively. Although literature provides numerous studies on the biodegradation of polymers of plant origin (PHA, PLA), the biodegradation of biomaterials based on petrol still requires further research and observations.

Mixtures of two or more polymers or copolymer materials that are not linked by covalence offer a viable alternative to reduce the costs of industrial products. Such mixtures, in various combinations, were used to produce traditional and biodegradable plastics, in order to improve some of the mechanical properties, to adjust the life cycle of the products to the needs and to lower manufacturing costs. Works on the methods of obtaining and modifying biodegradable polymers led to improved possibilities to use these material in the industry, construction and environment (Akrami et al., 2016;

Table 9
Characteristics and estimated degradation time of biopolymers.

Biopolymer	Source of origin	Properties	Composting time [days]	Degradation time [months]	Reference
Polylactide (PLA)	Sugar beet, corn starch, sugar cane, potatoes	• mildly hydrophobic • shows good compatibility with other polyesters, • maintains low moisture level, • good resistance to UV radiation, • low thermal stability (approx. 60 °C), • very good composite material, • may be composted, • increases stiffness of textiles, • low crystallization pace, • not toxic to the environment.	45–60	20	(Aliotta et al., 2017; Gupta et al., 2007; Lim et al., 2008; Murariu et al., 2015; Tokiwa and Calabia, 2006; Urbanek et al., 2017)
Polyhydroxyalkanoate (PHA)	Stored in bacterial cells as reserve material	• has good mechanical properties, • valuable biomass material, • light and easy to process, • high loading strength, • good resistance to UV radiation, • low water permeability, • not toxic to the environment.	–	12	(Boyandin et al., 2013, 2012; Shangguan et al., 2006; Wu, 2014)
Poly (ε-caprolactan) (PCL)	Petrol	• low resistance to UV radiation, • low melting temperature, approx. 60 °C • very good composite material, • high elasticity, • not toxic to the environment.	6–28	–	(Calil et al., 2006; Emadian et al., 2017; França et al., 2018; Prambauer et al., 2019)
Thermoplastic starch blends	Potato, corn, wheat, rice blending/mixing with other bio-based polymers (PLA, PCL)	• thermoplastic starch blends show more hydrophobic character, a lower water permeability and improved mechanical properties, compared to TPS, which prolongs degradation time even by 70%, • properties depend on composition, • low cost, • worldwide availability, • not toxic to the environment	45–56	–	(Dang and Yoksan, 2015; Du et al., 2008; Marinho et al., 2017)
Poly(hydroxylbutyrate) PHB	Produced and stored by bacteria	• brittle and stiff • high degree of crystallinity. Difficult to process, as its melting temperature is approx. 10 °C lower than degradation temperature • low impact strength • is susceptible to molecular degradation via hydrolysis at high processing temperatures • characterised by low chemical resistance. • modification possibility,	21–28	6–10	(Altaee et al., 2016; Javadi et al., 2010; Volova et al., 2015)
Poly(butylenesuccinate) PBS	Polycondensation reaction of 1, 4-butanediol with succinic acid	• high flexibility, excellent impact strength, and thermal and chemical resistance • very good composite material, • not toxic to the environment • mechanical properties, closely comparable to those of widely-used polyethylene (PE) and polypropylene (PP) • good processing capacity	67–90	–	(Kim et al., 2006; Kunioka et al., 2009; Mizuno et al., 2015; Zhao et al., 2005)
Cellulose acetate CA	Acetylation from wood pulp by applying acetic acid or its anhydride to cellulose	• medium mechanical properties, • ductile material, resistant to scratching • low scrub resistance • good insulation and anti-static properties • resistant to oils and fats. • good processing capacity	–	–	(Calil et al., 2006; Prambauer et al., 2019)

Bocchini et al., 2010; Iwatake et al., 2008).

Currently, the best known biopolymer is Polylactide (PLA). As a result, it attracts the most interest on the biopolymer market. In the last decade, its availability increased significantly, while the prices fell, which makes it a competitive material for most commonly available synthetics (Prambauer et al., 2019). What is important, the degradation process of PLA has been documented quite well not only in simulation tests, but also in practical conditions (Aliotta et al., 2017; Murariu et al., 2015; Tokiwa and Calabia, 2006). The main limitations that prevent using pure PLA are its brittleness and stiffness. However, this problem may be solved by mixing PLA with other biopolymers, including thermoplastic starch (TPS), or polyhydroxybutyrate-valerate (PHBV), which allows to apply it in nearly any environmental conditions (Ferri et al., 2016; Zhao et al., 2013). The example of PLA that is being increasingly used in commercial solutions demonstrates the need to continue wide-scale research on the application of other polymers, e.g. PHB, PBS, modified starch, modified PET and their mixtures, whose mass production or biodegradation processes in practical conditions are not sufficiently known yet in terms of industrial-scale production.

6. Conclusion

The growing production of polymer materials, caused by their ubiquitous applications puts an increasing pressure on the environment due to the load of non-biodegradable materials. Issues related to environmental protection, limited resources of fossil fuels, regulations or legislative authorities and the principles of sustainable development are some important reasons of the growing popularity of biodegradable materials. However, the amount of environmentally friendly polymers that appear on the market still remains decidedly lower than that of traditional, non-biodegradable polymers, and their production and applications are still unsatisfactory.

The analysis of literature and the state of technology reveals that biotextiles have a chance to become commonly used materials. This is also proven by growing interest on the market, and their competitive properties and the need to use them not only in innovative solutions, but also in widely understood environmental engineering.

There are several examples of plant and animal fibers that may provide a competitive alternative option for commonly used synthetic materials in short-term solutions. They include jute, coconut fiber or wool. These fibers are characterised by sufficiently good mechanical properties and low obtaining costs. Moreover, they decompose into elements that do not pose a risk to the environment and may even be used as plant fertilizer. One should also note that the data presented in literature are characterised by high discrepancies. They refer, among others, to High level of changeability of the chemical and mechanical properties of fibers, and the technology of their processing, which in turn affects the expected biodegradation time. In order to produce high quality natural fibers, the subsequent stages of obtaining, processing, technological treatment and storage must be systematised. This may contribute to increased repeatability of the properties of the final products. One may also state that the cost of natural fibers is low in comparison to artificial synthetic fibers. However, further research is required to analyse the costs of product development, field application, monitoring and evaluation of efficiency in order to estimate the economic benefits of this environmentally friendly approach.

The study also presents a review of the progress that has been made in research on biodegradable polymers in the last 19 years. It reveals that the main group of biosynthetic are biodegradable polymers obtained from renewable sources. Among them, Polylactide (PLA), which is currently one of the cheapest commercially available biopolymers, plays a dominant role. In this context, it is required to continue wide-scale research with use of other biopolymers, including PHB, PBS, modified starch, modified PET, and their mixtures. If biopolymers are introduced on a global scale, it will be necessary to eliminate their disadvantages by modifying and introducing new mixtures of the desired properties. At the moment, processes of modifying or combining several biopolymers are usually limited to single attempts in controlled conditions. Such level of knowledge of the properties of biopolymers is insufficient to introduce them on the market on a mass scale and to increase the profitability of mass production. The process of manufacturing and modifying biopolymer fibers requires a series of studies in order to determine the best possible solutions for specific materials and to improve the technological, economic, and environmental efficiency of the manufacturing of selected products. In this light, the perspective of creating a global market of biopolymers may become more realistic.

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.

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Załącznik nr 3 do Trybu postępowania w sprawie nadania stopnia naukowego doktora

Daria Marczak
imię i nazwisko

Wrocław, 04.09.23r.
miejscowość i data

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OŚWIADCZENIE

Oświadczam, że w pracy ***Marczak D.**, Lejcuś K., Misiewicz J. 2020. Characteristics of biodegradable textiles used in environmental engineering: a comprehensive review. Journal of Cleaner Production. 268, 122129. DOI:10.1016/j.jclepro.2020.122129,* mój udział polegał na zaproponowaniu i tworzeniu koncepcji oraz planu publikacji, określeniu celu i zakresu, wyszukiwaniu i gromadzeniu danych, analizie uzyskanych danych, dokonaniu przeglądu literatury. Otrzymane wyniki opracowałam pod względem merytorycznym, przygotowując manuskrypt oraz wizualizację wyników, a następnie uczestniczyłam w redagowaniu tekstu w procesie recenzji i opracowaniu ostatecznej wersji publikacji.

Byłam wykonawcą w projekcie pt. Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin (nr POIR.04.01.04-00-0061/16; Narodowe Centrum Badań i Rozwoju), obejmującym badania zaprezentowane w niniejszej pracy.

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Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation

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ABSTRACT

Due to the growing awareness and the need to reduce the environmental impact of textiles, there is a pressing rationale to use natural materials or fibres in environmental engineering. One solution to achieve energy sustainability is to develop sustainable technologies to gradually replace non-renewable fossil fuels. One of technology is water-absorbing geocomposite (WAG). WAG is an innovative technology that supports water management and the vegetation of plants and is used, among others, in environmental engineering and agriculture. WAG can be produced in biodegradable WAG version, which is also environmentally friendly. The paper provides an evaluation of the influence of time of installation and biodegradation on the mechanical, hydraulic, and chemical properties of used textiles. The biodegradation of geotextiles was analyzed in real time, and their parameters were determined after one vegetation season. Needle-punched nonwovens made from wool and linen or reinforced by jute mesh were biodegraded already after the first vegetation season. Significantly better mechanical properties were observed in nonwovens produced from the same materials, but reinforced by seams. All types of geotextiles were characterised by sufficient resistance to biodegradation that allowed maintaining vegetation and proper operation of WAG at least for one vegetation season. Biodegradable geotextiles installed in soil provide instantaneous protection, and their gradual discomposure fosters plant vegetation.

1. Introduction

In recent years, concerns over the large amount of solid waste associated with conventional polymers have raised public awareness of the extensive use of petroleum-derived polymers. Human economic activity influences the environment directly and indirectly, often leading to changes that result in its degradation [10,44]. This also refers to geotextiles used in environmental engineering, construction or hydraulic engineering. Wide range of available geotextiles, which are usually relatively cheap and easy to install, has attracted designers and contractors due to the possibility to make significant savings in comparison to other engineering solutions [4,50]. According to estimations, nearly 1500 million square meters of geotextiles are used each year [39]. Such a great demand results from the numerous advantages and wide range of applications of these materials. Geotextiles may perform mechanical (separation, reinforcement, strengthening, anti-erosion protection), hydraulic (filtration, drainage), and biological functions (protection, reclamation) [16,30,36]. They are also applied in agriculture as fertilizers or materials that improve retention [6].

Depending on manufacturing technology and the function performed by geosynthetics, they may take the form of sheets, bands or spatial forms. They are applied in geotechnical engineering in combination with soil or other materials. Among the wide range of geotextile manufacturing technologies and performed functions, nonwovens are the most commonly applied group, due to their significant porosity, water permeability and resistance [27,39].

Depending on their designation, geotextiles may be produced from synthetic or natural materials [22,42]. The environmental engineering and construction sectors are the main consumers of raw materials and energy, which vastly contributes to environmental pollution. Geotextiles play a significant role in water and energy sustainability. Besides addressing water and energy scarcity, meet sustainability criteria in terms of environmental impacts, land usage, ease of use, flexibility and adaptability [23,31]. Pursuant to the principles of sustainable development, the construction industry will have to accept the reuse of by-products and recyclable materials [33,36,44]. The selection of geotextiles depends on the hydrogeological conditions and the functions that the material should perform [26,48]. Most geotextiles are manufactured from PP,

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PET, and PE, which are not degradable and maintain their properties for at least a dozen years, but, on the other hand, are harmful for the environment [15,49]. The search for sustainable alternatives for technological development has progressively increased interest in research that approaches the use of renewable materials and the reuse of materials [29]. For short-term applications, it would be desirable to select such alternative materials as natural fibres or biodegradable polymers. They are most often produced from animal or plant based materials, such as sheep wool, jute, linen or coconut fibre [40,41,43,45,46]. When installed in soil, they provide instantaneous protection, and their gradual biodegradation fosters the vegetation of plants and is safe for the environment ([8,28,53]). However, in spite of their potential, they still have a small percentage share in the overall geotextile production. The installation of geotextiles made from natural materials in the environment is justified by the hydrophilic properties of fibres and relatively short degradation time which, however poses certain limitations in engineering practices. Nevertheless, it is estimated that non-biodegradable materials may be replaced by environmentally-friendly geotextiles based on animal or plant materials even in 50% of all engineering applications [12,39].

Water and energy are fundamental resources used for economic and social development. These resources have been long presupposed as abundant. With the increase of population and the developments brought by the industrial revolution, their demand increased and scarcity is now an undeniable result. One solution to achieve energy sustainability is to develop sustainable technologies to gradually replace non-renewable fossil fuels [23]. The water-absorbing geocomposite (WAG) is a new type of geosynthetic. WAG is a novel technology retaining soil water that is available for plants. It is a spatial structure capturing water in the soil and retaining it inside in the form of a gel. It consists of a nonwoven that captures the water infiltrating into the soil and transports it inside the WAG. This water is then absorbed by the superabsorbent. The skeleton structure enables the free swelling of the gel, providing the necessary space that allows for the absorption of water or its solutions by the superabsorbent without being affected by the stress resulting from the load of soil above it. This space enables to fully benefit from the properties of superabsorbents [25]. It was also found that direct mixing of superabsorbents with soil significantly reduces water absorption, which is caused by soil load [25,32]. Plant roots can grow through the textile and uptake up to 95% of stored water [35]. The process of retaining and collecting water can occur repeatedly [24]. WAGs may be manufactured from either synthetic or biodegradable materials. The application of WAG had a positive influence on improving the erosion control by enhancing the development of the root systems of grass and bushes and improving soil shear strength on the slope of the test embankment. It also reduced evaporation from soil and increased the biomass of selected perennials [3,9,24,37,51]. WAGs increased biomass of grasses in process of tailing ponds biological stabilization [18,20].

The necessity to limit the consumption of non-renewable resources and reduce environmental pollution resulted in a growing interest in the subject of biodegradation of geotextiles based on plant and animal fibres and biopolymers. However, as water absorbing geocomposites have been used for a relatively short time, no research has yet been conducted on the application of biodegradable geotextiles in this product. The aim of our research is to determine the phenomena that accompany the biodegradation of geotextiles used in the new generation of water absorbing geocomposites. Geotextiles were analyzed in a soil test in actual field conditions. Their mechanical, hydraulic and chemical properties were analyzed before and after the biodegradation process and the degree of biodegradation after one vegetation season was determined. Overall, advances in material development are far ahead of an understanding of lifetime analyses of this emerging biodegradable composite material. It is therefore necessary to fully characterise the biodegradability of elements of water absorbing geocomposites in practical real-life contexts such as in soil under ambient outdoor conditions.

2. Materials and methods

2.1. Materials

The prototypes of water absorbing geocomposites in form of mats of the dimensions 0.22 × 0.22 m consisted of: wooden internal skeletons (0.20 × 0.20 × 0.02 m), Aquasorb 3005 KL superabsorbent and biodegradable geotextile serving as a sheath – WAG (Table 1, Fig. 1). Aquasorb 3005 KL (SNF FLOERGER, Andrézieux, France) is a cross-linked *co*-polymer of acrylamide and potassium acrylate, which is sensitive to environmental factors and undergoes gradual biodegradation as a result of the influence of selected soil bacteria [35].

2.2. Research locations

The experiment was started in May 2018 on an experimental field located in the area of the Agricultural and Hydrological Observatory Wrocław-Swojec (51°07′N, 17°10′E, elevation 121 m a.s.l.) of the Wroclaw University of Environmental and Life Sciences. It is located in south-western Poland, in moderate climate zone. The total annual precipitation in the lowlands of Lower Silesia is 560÷600 mm [38].

Prototypes of biodegradable water absorbing geocomposites were made from strips of nonwoven of the dimensions of 0.44 × 0.22 m, which were sewn together with a sewing machine so as to create square mats (0.22 × 0.22 m). These mats were later filled with a wooden skeleton (0.20 × 0.20 m) and dry SAP and then closed. The applied dose of superabsorbent was sufficient to ensure that it would fill the whole capacity of the WAG after swelling. Before installing in soil, the prepared WAG prototypes were soaked in water and placed in a hole whose walls were secured by a synthetic cover of a diameter of 0.20 m. Such preparation of sites allowed us to control the growth of the root mass. Then the WAGs were covered with a 0.15 m thick layer of fertile soil (humus) with granulation of sandy loam (Fig. 2). The tested soils were classified according to the USDA classification.

All sites were sown with the same amount of grass mixture (0.63 g/sample, which corresponds to 200 kg/ha), composed of:

Table 1
Characteristics of the analyzed material.

Item	Sample name	Composition of raw material	Manufacturing technology
1.	BA	99.4% washed wool +0.6% synthetic seams	seamed textile (synthetic seams, tricot weave)
2.	BB	100% washed wool	needle-punched nonwoven
3.	BC	90% washed wool + 10% jute	needle-punched nonwoven + jute mesh
4.	BD	49.7% washed wool + 49.7% linen+0.6% synthetic seams	seamed textile (synthetic seams, tricot weave)
5.	BE	50% washed wool + 50% linen	needle-punched nonwoven

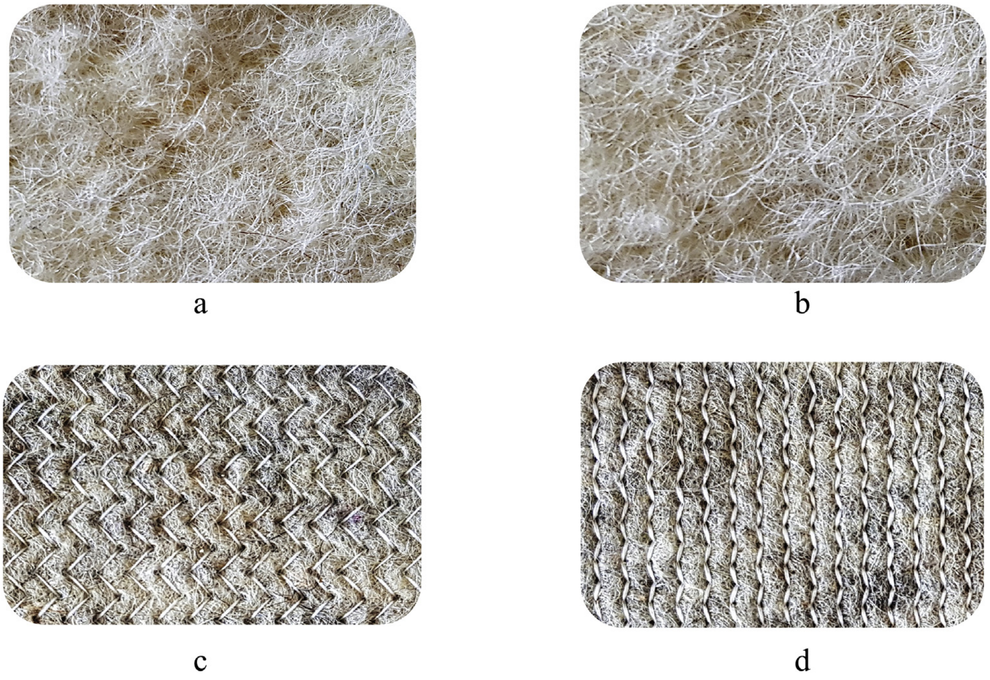


Fig. 1. a, b. Needle-punched nonwoven, 100% wool (right and wrong sides). c, d. Seamed geotextile 99.4% washed wool +0.6% synthetic seams (right and wrong side).

- Perennial ryegrass (*Lolium perenne*) 65%
- Kentucky bluegrass (*Poa pratensis*) 5%,
- Red fescue (*Festuca rubra*) 20%,
- Sheep fescue (*Festuca ovina*) 5%.

The temperatures in the analyzed period (May–October) ranged from 5.1 °C (October 2018) to 25.9 °C (August 2018) (Fig. 3). The highest monthly precipitation was noted in July (72.9 mm), and the lowest (11.4 mm) in August (Fig. 4). During the whole analyzed period, 38 days with precipitation above 1.0 mm were noted. The highest rainfall (30.1 mm) was noted in June. The average temperature in the analyzed period was 16.6 °C, which was 1.7 °C higher than the long-term average (1971–2000). The total precipitation in the analyzed period was 282.1 mm and it was 86.8 mm lower than the long-time value (1971–2000) [55].

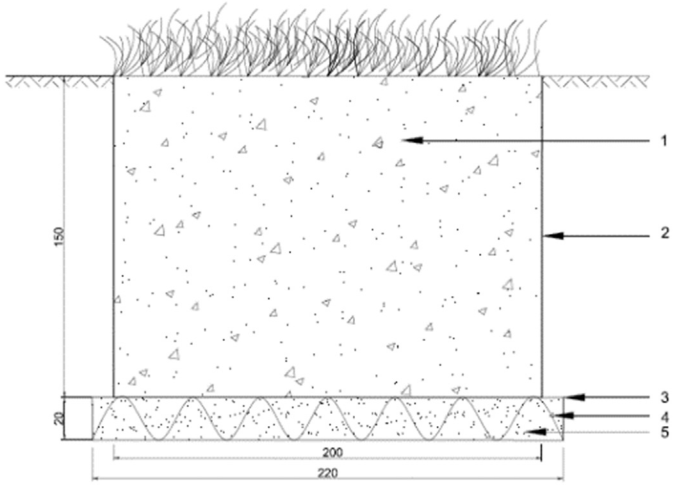


Fig. 2. Cross section of the test stand: 1-soil, 2-synthetic cover, 3-nonwoven, 4-internal structure 5-superabsorbent.

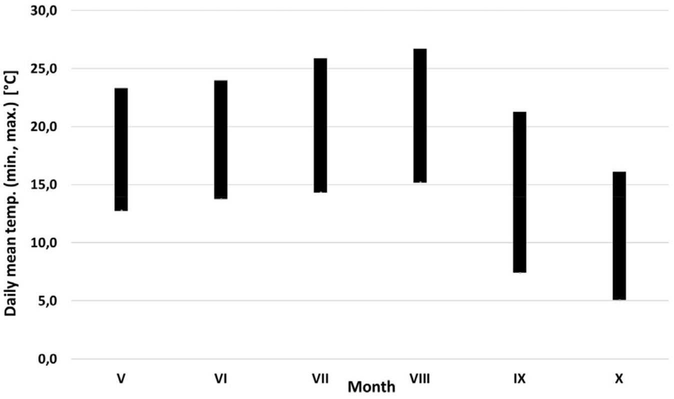


Fig. 3. Distribution of extreme daily temperatures in individual months in the analyzed period.

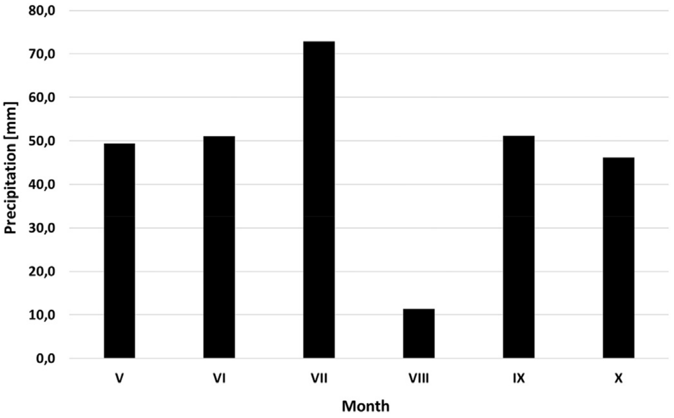


Fig. 4. Distribution of total monthly precipitation in the analyzed period. "The authors used meteorological data from the Faculty Agricultural and Hydrological Observatory Wrocław-Swojec (WOAiHW-S)."

Fig. 5. Preparation of the sample for laboratory tests.

2.3. Preparation of geotextile samples for analysis

Each type of geotextile was applied in 18 iterations, with a random selection of their placement on the experimental field, so as to avoid the influence of boundary conditions. Nonwovens were provided by the manufacturer in form of rolls. Samples were prepared by cutting fragments of the material with the exception of the area of approx. 0.10 m along the edge of the roll in order to avoid the potential influence of technological parameters on degradation time. Table 4 presents the results of tests of physical and mechanical properties of the model geotextiles used for the production of WAGs. Tests were conducted on nonwovens of a surface mass ranging from 287 g/m^2 (BB) to 368 g/m^2 (BC) and thickness from 2.3 mm (BD) to 3.5 mm (BC).

After the end of the vegetation season, samples of nonwovens were collected from the test field together with the geocomposite and root mass of grass. Then, the geotextiles were separated from the other elements of the geocomposite, dried at room temperature and thoroughly mechanically cleaned to remove plant roots and soil particles (Fig. 5).

2.4. Research methodology

In order to evaluate the influence of operation time on biodegradation, the physical, mechanical, and hydraulic properties of the tested material were assessed. Tests of parameters were conducted in compliance with the procedures provided in the relevant harmonized standards concerning geotextiles (Table 2).

The chemical composition of fibres was analyzed with use of Fourier transform infrared spectroscopy (FTIR). The Thermo Scientific Nicolet iS5 FTIR spectrophotometer with a transmission module was used. Spectra were recorded on approx. 1 mm long sections of natural fibres

Table 2
Methods used in research.

Parametr	Sample size [m]	Equipment	Brief characteristics	Method
Surface mass of geotextiles	0.10 × 0.10	Analytical balance	The surface weight of samples was determined with the accuracy to two significant figures, according to the formula: $M_p = \frac{m}{s \cdot l}\left[\frac{g}{m^2}\right]$ where: m – sample weight, g; s – sample width, m; l – sample length, m	EN ISO 9864:2005
Thickness according (load 2 kPa,20 kPa)	0.10 × 0.10	Thickness gauge with digital display for textiles	Thickness was determined by placing a nonwoven sample directly below the measurement foot of the stationary thickness meter and loading it additionally with a load of pre-defined weight. The thickness of samples was read from the digital display of the meter.	EN ISO 9863-1:2016
Static puncture (CBR test)	Ø 0.15	Static CBR Puncture Testing Machine	Static puncture was determined by means of mounting the sample between two steel rings in the CBR apparatus and loading it gradually with a metal bolt of the diameter of 0.05 m, pressed into the sample at a constant speed of 50 mm/min, The test was conducted until the moment when the bolt punctured the sample. The result of the measurement is the value of puncturing force (kN).	EN ISO 12236:2006
Dynamic perforation test (cone drop test)	Ø 0.15	Drop Hammer Penetrate Tester (Cone drop test, Dynamic perforation test)	Dynamic perforation was determined by placing the sample between two steel rings and lowering a steel cone weighing 1 kg onto its central part from the height of 0.50 m. The perforation size was measured with use of a scaled measurement cone. The result of the measurement is the diameter of the created hole (mm).	EN ISO 13433:2006
Water permeability characteristics normal to the plane, without load	Ø 0.05	Vertical Permeability Tester For Geotextile	Water permeability was determined by subjecting the sample to water flow, directed perpendicularly to its surface at a decreasing height of hydraulic pressure. The test started at water pressure H = 0.35 m and ended at H = 0.00 m. Average flow rate was calculated from the selected range of water level and a diagram was created.	EN ISO 11058:2019

cut out of the textiles and pressed in KBr pastilles. The pastilles were prepared by mixing fibre sections with KBr dust and then pressing them under a pressure of 20 MPa. The reference background was the spectrum of KBr pastille. The reference spectrum was deducted proportionately to the mass of KBr in a pastille with fibre sample in comparison to the KBr mass in the reference pastille. Spectra were recorded in the range from 400 to 4000 $\mathrm{cm^{-1}}$ at the resolution of 4 $\mathrm{cm^{-1}}$ and 32 scans. Spectra were then subjected to mathematical processing in order to enable qualitative and quantitative comparison. After recording, the spectra were processed in order to remove interferences caused by the presence of atmospheric water vapour and carbon dioxide. Interferences were reduced with use of spectrum derivatives and the background scattering in characteristic local minima of the spectra was separated. Spectra were reduced to identical integrated surface below the diagram in the wavenumber range from 4000 $\mathrm{cm^{-1}}$ to 400 $\mathrm{cm^{-1}}$.

3. Research results

3.1. Physical and mechanical properties of nonwovens and fibres

Table 3 contains photos of model nonwovens and the material 6 months after installation (before and after the biodegradation process). The analysis of the obtained test results presented in Table 3 reveals that as far as needle-punched nonwovens are concerned, regardless of the raw material used, the material was subject to strong biodegradation 6 months after installation. The biodegradation of needle-punched nonwovens was so advanced that the material could be easily torn by hand, and the fibres had become brittle and lost their elasticity. In certain locations, only remains of the geotextile that were difficult to separate were found.

As a result of intense biodegradation, needle-punched nonwovens lost their integrity and after removing particles of soil only single fibres remained left. Such condition of the samples made it impossible to carry out tests of both physical properties and strength of the material. Only chemical parameters were possible to determine. In spite of the loss of integrity in nonwovens without seams, after several months the grass root system had formed so well that it had grown into the inside of the geocomposite, forming a cohesive structure and enabling its further, smooth operation (Fig. 6).

After the vegetation season, all analyzed nonwovens were partly or completely biodegraded. Table 4 presents, among others, the results of tests of physical and mechanical properties of geotextile that were subject to biodegradation 6 months after installation.

Fig. 6. Grass root system that formed on needle-punched nonwoven, 100% wool (BB).

As a result, the determination of the influence of operation time of nonwovens on selected properties of the product was possible only for seamed nonwovens, regardless of their composition (samples BA and BD).

Nonwovens BA and BD retained their mechanical integrity and performed their functions as elements of WAG correctly, in spite of a noticeable loss of mass. Geotextile BA showed a significant loss of keratin fibres, discolouration and signs of rotting. However, the synthetic wrap remained intact. Samples of seamed geotextile BD showed characteristic discolouration in some places as well as fibre loss.

The highest reduction in surface mass, over 84%, was noted for seamed nonwoven BA. As far as geotextile BD, the mass loss decreased by 54%, 6 months after installation. Both seamed nonwovens were

Table 3
Photographs of nonwovens used in the study before and after the experiment.

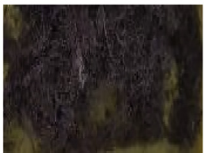
MONTHS	MATERIAL TYPE				
	BA	BB	BC	BD	BE
„0”					
„6”					

Table 4
Physical and mechanical parameters of nonwovens used in WAGs before and after the biodegradation process.

Material type	Months	Surface mass [g/m^2]	Thickness [mm]		Dynamic puncture strength (cone) [mm]	Static puncture strength (CBR) [N]
			2 kPa	20 kPa		
BA	0	368	2.4	1.6	20	540
	6	57	1.1	0. 8	33	140
BB	0	287	3.3	1.5	24	40
	6	–	–	–	–	–
BC	0	333	3.5	1.9	16	270
	6	–	–	–	–	–
BD	0	289	2.3	1.5	23	620
	6	134	1.2	0.7	37	200
BE	0	308	2.9	1.5	31	40
	6	–	–	–	–	–

characterised by similar thickness before (2 kPa: BA–2.4 mm, BD-2.3 mm) and after biodegradation (2 kPa: BA-1.1 mm, BD-1.2 mm).

Further analyzed mechanical properties of fibres were their static and dynamic puncture strength. After the end of the experiment, the static puncture strength for BA geotextile decreased by 75%, while for BD geotextile it fell by 32%.As far as dynamic puncture strength is concerned, it increased from 20 mm to 33 mm for the BA sample, while for the BD sample it increased from 23 mm (model) to 37 mm (after 6 months). Regardless of the type of raw material used, the dynamic puncture strength measured with the cone method was very similar for both types of nonwovens and it decreased by over 60% (BA-65%, BD-61%).

3.2. Hydraulic properties of nonwovens used to produce WAG

In order to determine the changes in filtration properties of nonwovens depending on their composition, manufacturing technology, and operation time, water permeability normal to plane and product were conducted. The obtained test results are presented in Table 5 and in diagrams 7–8.

The analysis of the obtained results of the influence of operation time on the filtration properties of nonwovens used to produce the WAG geocomposite after 6 months from installation in soil revealed that it was impossible to collect test material from needle-punched nonwovens due to the degree of their biodegradation. As far as seamed geotextile made from 99.4% wool was concerned, the initial water permeability normal to plane was 74.7 mm/s. After the vegetation season, the water permeability of the geotextile increased by 43% (106.6 mm/s). The water permeability of the model seamed geotextile BD was 60.9 mm/s. six months after installation, the value of this parameter was 79.1 mm/s, which means an increase by approx. 30%.

3.3. Changes in chemical structure after biodegradation

The applied spectral recording method does not have a significant influence on the supermolecular structure of the analyzed fibres. They retain their shape and form in the process of preparing for spectrum recording. The observed differences in the recorded spectra should rather be interpreted as a resultant of the influence of changes in the chemical and supermolecular structure of the analyzed samples. The presentations of spectra additionally contain the differences between spectra after and before the biodegradation process at a 1÷1 proportion.

Table 5
The results of the measurement of water permeability characteristics normal to plane of nonwovens.

Number of months	Water permeability normal to plane (filtration speed)	Material type				
		BA	BB	BC	BD	BE
0	**X [m/s]*10^{-3}**	**74.7**	**94.5**	**83.3**	**60.9**	**69.9**
	S [m/s]*10^{-3}	4.9	3.5	4.7	5.0	20.4
	V[%]	6.6	3.7	5.6	8.2	29.1
6	**X [m/s]*10^{-3}**	**106.6**	–	–	**79.1**	–
	S [m/s]*10^{-3}	2.8	–	–	6.0	–
	V[%]	2.6	–	–	6.1	–

Where: X- average value, S- standard deviation, V- coefficient of variation.

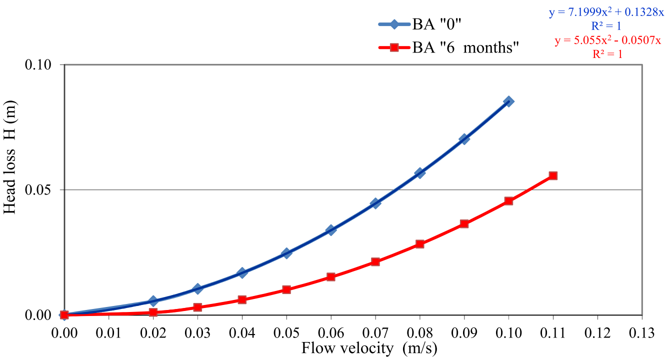


Fig. 7. Flow velocity characteristics of tested nonwoven geotextile samples (BA): (BA"0″) raw fibres; (BA"6 months") after the growing season.

The FTIR spectra of the analyzed fibres showed typical bands assigned to oscillators of groupings in the amide group –CO-NH-. For the C=O oscillator it was approx. 1650 cm^{-1} and C–N with a deformative N–H at approx. 1580 cm^{-1} (Fig. 5-9). All samples showed a characteristic wide band of oscillators of the –OH and N–H groups that enter strong intermolecular forces, and, as a result, are present in a wide range of spectrum, approx. 3800÷2000 cm^{-1}. The wavenumbers 3280÷3250 cm^{-1} show bands characteristic for C–H group oscillators. For raw fibres before installation of WAG in soil, amide bands I, II, and III for samples containing 100% wool (BA, BB) were present, respectively, at 1658 cm^{-1}, 1503 cm^{-1} and 1233 cm^{-1}. In BA and BB samples, at wavenumbers of approx. 1077 cm^{-1}, a band corresponding to the S–O bond oscillator was observed. It was less intensive for raw BB geotextile than after the biodegradation process [8,52].

The FTIR spectra of fibres obtained from BD and BE samples are presented in Figs. 12 and 13. The –OH group is one of the functional groups in cellulose and the typical absorption bands are present in spectra of samples that contain plant fibres. The area between 3800 and 2500 cm^{-1} showed an absorbance of bands connected with stretching oscillations of OH groups (3800–3000 cm^{-1}) and the CH group (3000–2500 cm^{-1}) in the fibre structure. OH groups are present in cellulose, hemicellulose and lignin. Bands in the range of wavenumbers from 1890 cm^{-1} to 1580 cm^{-1} are characteristic, among others, for carbonyl groups that are present in the structures of hemicellulose and lignin (Marques et al., 2014).

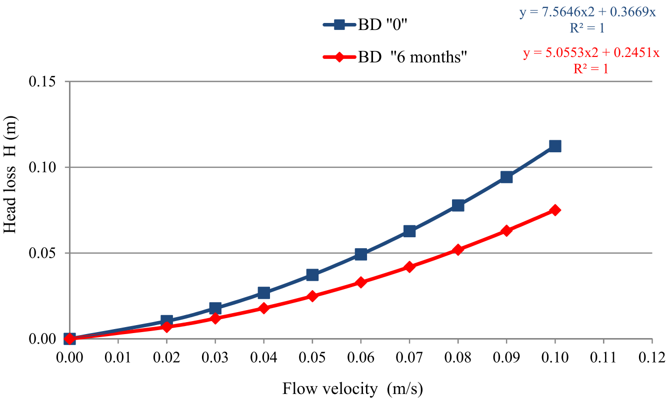


Fig. 8. Flow velocity characteristics of tested nonwoven geotextile samples (BD): (BD"0″) raw fibres; (BD "6 months") after the growing season.

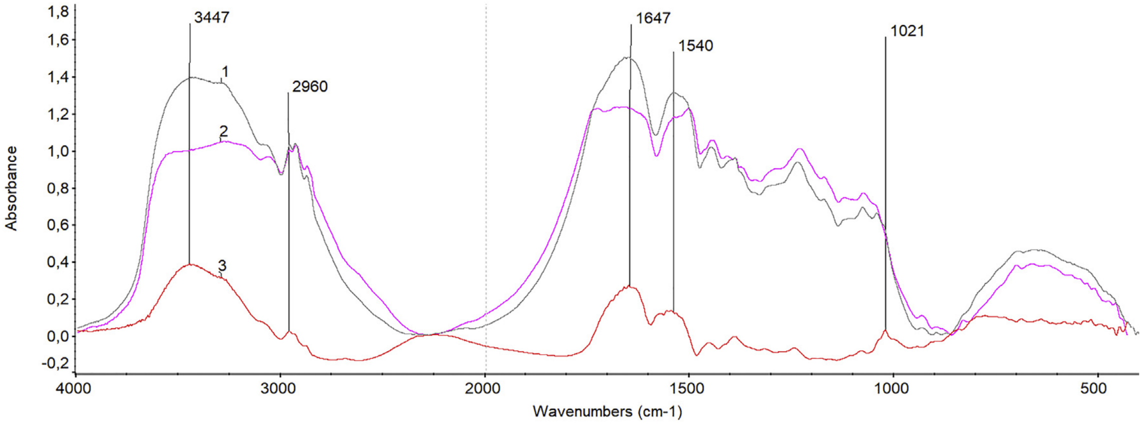


Fig. 9. FTIR spectra of woollen geotextile BA (1) initial textile; (2) after the vegetation season; (3) differences in the BA textile spectra before and after biodegradation.

The analysis of the shape of spectra before and after biodegradation, together with the difference between spectra, points, first of all, to the loosening of intermolecular structure. The differential spectrum contains local maximums in the locations of oscillators of groups that participate in intermolecular forces, mainly hydrogen forces. The changes in wool spectrum after the biodegradation period occurred in a small band in the area of oscillators of C–O and S–O bonds (in the position of approx. 1021 cm^{-1}), which demonstrates protein oxidation. The shift of the band at approx. 1540 cm^{-1} towards higher wavenumbers points to the decomposition of organised areas of keratin (Fig. 9). The biodegradation of wool fibres demonstrates rather a gradual depolymerisation connected with the swelling of the material. This mechanism might confirm a gradual release of components rich in nitrogen while maintaining the characteristic chemical structure of keratin.

The analysis of spectra of woollen geotextile BB shows similar features of chemical decomposition and swelling of the supermolecular structure (Fig. 10). What is characteristic is stronger oxidation of the material in form of a high spectral difference band at the position of approx. 1020 cm-$^{1.}$

The analysis of the spectra of woollen geotextile with an addition of jute demonstrates that the plant component has a significant influence on the spectra (Fig. 11). Jute undergoes biodegradation faster than wool. Characteristic differential bands appear at approx. 3400 cm^{-1}; 1697 cm^{-1}; 1200 cm^{-1} and 1100 cm^{-1}. These bands are a result of hydrolysis of polysugars. As a result of the decomposition of glycosidic bridges, C–O and O–H groups emerge. The biodegradation of the plant component is part of the mechanism of the cellulose chain degradation.

The spectral analysis of samples of nonwovens produced from mixtures of wool and linen demonstrates, as before, an accelerated decomposition and biodegradation of the cellulose chain as a result of the hydrolysis of the glycosidic bond (Fig. 13). As the biodegradation of wool probably consists in gradual depolymerisation, the results in spectral images are slight and not visible in the presence of the results of cellulose hydrolysis.

4. Discussion

The selection of the specified composition of nonwovens was based on the earlier literature review, where the positive properties of these materials in field applications were often mentioned.

Jute geotextiles are commonly used to protect soil from negative external influences, due to their elasticity, strength and easy processing and installation [41,48]. On the other hand, linen fibres have an outstanding tensile strength, and, what is characteristic, their strength increases when wet, which makes them an attractive material for locations exposed to contact with water [2]. Woollen geotextiles are commonly used for anti-erosion protection and in agriculture. They minimise evaporation, provide thermal protection, and their degradation process releases compounds rich in nitrogen and phosphorus to the soil [5,7,54]. In moist soil environment, the fibres were exposed to the direct influence of enzymes released by microorganisms. Their development was fostered by positive air temperatures that were noted throughout the analyzed period. The microorganisms present in soil initially attach the scales that cover the fibre core, making it extremely susceptible to microbiological degradation [6,19]. These processes are

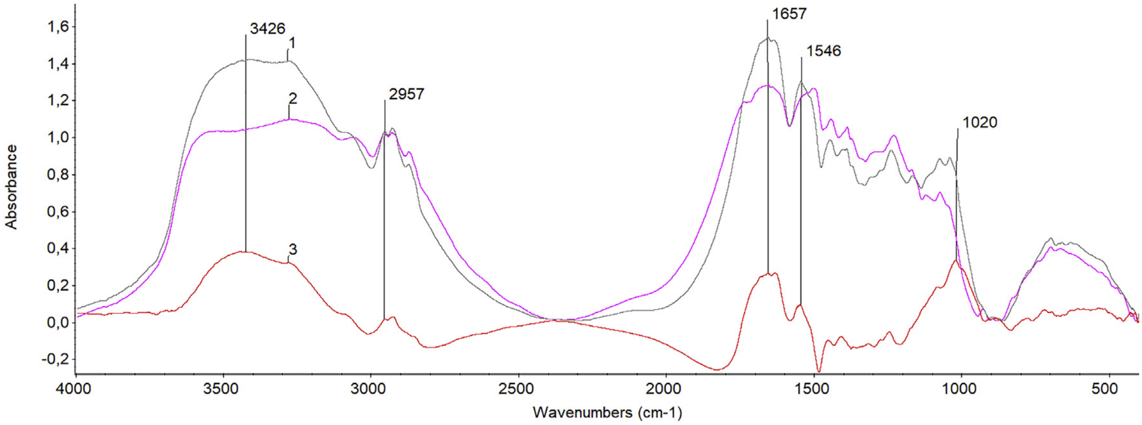


Fig. 10. FTIR spectra of woollen geotextile BB (1) initial textile; (2) after the vegetation season; (3) differences in the BB textile spectra before and after biodegradation.

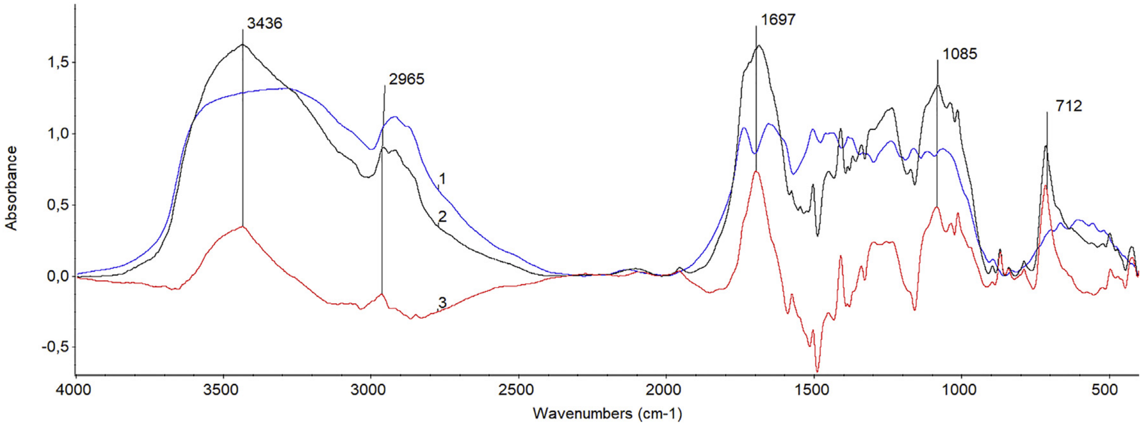


Fig. 11. FTIR spectra of woollen geotextile on jute BC (1) initial textile; (2) after the vegetation season; (3) differences in the BC textile spectra before and after biodegradation.

manifested in a significant decrease in the mechanical parameters of samples. In textiles BB, BC, and BE, the biodegradation process was faster, and the fibres were brittle, so it was difficult to obtain an intact sample. Such quick pace of biodegradation may be explained by their application in specific WAG conditions: at high moisture content and in the presence of intensively growing plant root systems. WAG enables water retention and reduces its infiltration into deeper layers of the soil profile. Research has confirmed that WAG indeed contribute to increased moisture content in soil, which, as a result, may foster the development of microorganisms and accelerate fibre destruction [47]. Broda et al. [7] confirmed that the biodegradation process was intensified in geotextiles exposed to direct contact with water. The experiment was conducted on ropes manufactured from woollen by-products, installed on the banks and bottom of a drainage ditch. Tests demonstrated that already after 6 months of operation the static puncture resistance of geotextiles installed at the bottom, where samples were exposed to direct contact with water, fell by nearly 90%, while on the slope it decreased by 75%. The value of dynamic puncture strength decreased, respectively, by 44% and 19%.

The present research revealed a significant increase in the water permeability normal to plane of nonwovens. This is caused by the intensified influence of the biodegradation process of nonwovens that were exposed to atmospheric factors, as well as to direct contact with soil and colonisation of fibre surface by microorganisms. This phenomenon also results from the intensive development of grass root system. These factors led to a significant loss of mass of the analyzed material, and thus to an increase in water permeability. At the same time, Grzybowska-Pietras et al. [13], in their studies on the application of woollen ropes in anti-erosion protection of slopes, noted a significant decrease in water permeability already after 6 months of operation. The water flow rate through woollen geotextile decreased by approx. 37%, which resulted from clogging of the material by soil particles. In this study, samples collected from the inside of ropes might have had limited contact with microorganisms, and thus the process of biodegradation was slower.

The comparative analysis of FTIR spectra of raw samples and samples after the vegetation season confirmed that with the biodegradation process the keratin protein starts to decompose and transform into biomass that may be absorbed by the root system. After the cover structure has been degraded, enzymes penetrate inside the fibre causing decomposition, which is shown in the FTIR spectra. The observed shifts of the Amid I ad Amid II bands are characteristic for loosening the supermolecular structure. The intensification of these bands after biodegradation is another characteristic phenomenon caused by the increased likelihood of interaction with grouping oscillators of the amide group of the measuring beam in the loosened spatial structure. Absorption bands connected with stretching oscillations of OH before and after the biodegradation process in BD and BE samples demonstrate the difference in their molar content and their participation in intermolecular interactions. The changes refer mainly to the positions in the range 3800÷2500 cm^{-1}, which are assigned, respectively, to OH and NH groups. It was noted that the bands in these ranges increased absorption intensity after several months of operation in soil. The difference in the absorption levels may be explained by the differentiation in the share of hydrogen forces in the supermolecular structure of the fibre material caused by the progressing biodegradation process [14,17].

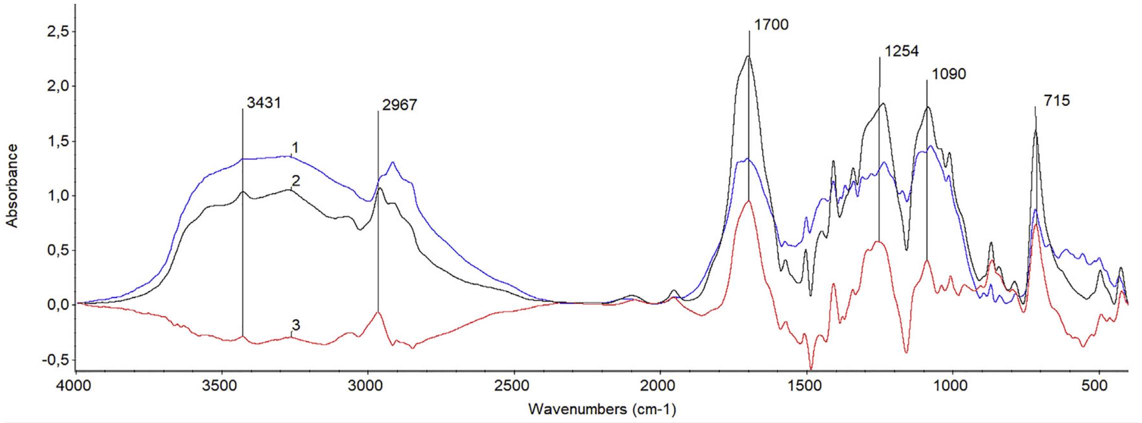


Fig. 12. FTIR spectra of woollen geotextile with linen BD (1) initial textile; (2) after the vegetation season; (3) differences in the BD textile spectra before and after biodegradation.

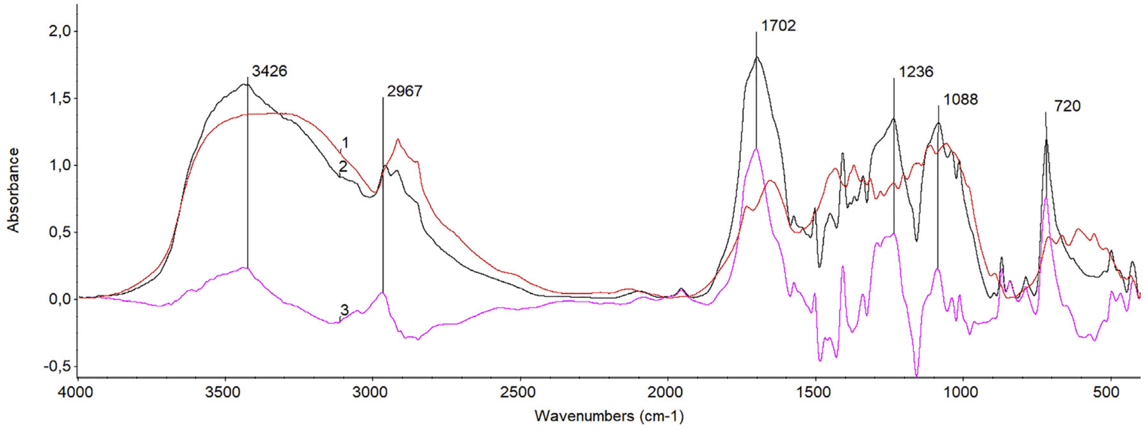


Fig. 13. FTIR spectra of woollen geotextile with linen BE (1) initial textile; (2) after the vegetation season; (3) differences in the BE textile spectra before and after biodegradation.

In the research by Broda et al. [8], the analysis of amide bands in FTIR spectra revealed that wool fibres did not undergo significant biodegradation during the first six months of operation. Studies on the biodegradation of the superabsorbent in WAG confirmed an intensive colonisation by bacteria and fungi, which cause its gradual degradation and may at the same time deposit on the geotextile [34]. Alimuzzaman et al. [2] analyzed the progress of biodegradation of linen and its biocomposites. They found that linen fibres were subject to rapid degradation already after the first month of operation. Ultimately, the sample produced mainly from linen was completely biodegraded already after 4 months. Biodegradation was caused first of all by enzymes released by microorganisms existing in soil.

In this work, a much higher resistance to biodegradation of nonwovens made of a mixture of linen and wool reinforced with seams (BD) was observed. Flax fibres contain about 70–75% cellulose, 18–20% hemicellulose, 5–10% lignin and wax. The presence of these ingredients determines the higher microbiological stability and high tensile strength, even in wet conditions [1,11,21].

5. Conclusions

Nonwovens used in water absorbing geocomposites may be successfully manufactured from commercially available biodegradable materials of animal or plant origin. Due to their increased water retention capacity and gradual release of nutrients to soil, natural fibres foster the development of plant root system. The process of biodegradation of sheep wool is relatively slow, and in combination with cellulose-based materials, it creates beneficial conditions for plant growth and offers the possibility to extent the biodegradation duration to at least two vegetation seasons. Such time should be sufficient for germination, rooting and growth of plants that are typically used for the protection of slopes, perennial ornamental plants, or crops in agriculture.

Structural degradation of nonwovens without seams BB, BC, and BE, took at least 6 months. During this time, the nonwovens lost their integrity, and the fibres became brittle and difficult to isolate from soil. During the biodegradation of the nonwovens used, a gradual destruction of fibre structure was observed. As the progressing biodegradation was accompanied by a gradual release of vegetation supporting compounds, the root system of grass managed to develop sufficiently to maintain the potential of WAG for the subsequent vegetation season. Nonwovens BA and BD that contained additional seams, were characterised by much higher mechanical strength. The seams improved the elasticity of the material and thus enhanced its mechanical parameters, even after several months of operation in soil.

The nonwovens presented in this paper were characterised by sufficient resistance to biodegradation to maintain vegetation and the proper functioning of WAG for at least one vegetation season. The application of natural materials improves water retention, supports the growth of plants and is environmentally friendly.

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.

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OŚWIADCZENIE

Oświadczam, że w pracy ***Marczak D.,*** *Lejcuś K., Grzybowska-Pietras J., Biniaś W., Lejcuś I., Misiewicz J. 2020. Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation. Sustainable Materials and Technologies. 26, e00235. DOI:10.1016/j.susmat.2020.e00235,* mój udział polegał na zaproponowaniu i tworzeniu koncepcji oraz planu badań, sporządzeniu przeglądu literatury, przygotowaniu materiału badawczego, założeniu i prowadzeniu doświadczenia terenowego, doborze metodyki badań, określeniu parametrów wytrzymałościowych, hydraulicznych i chemicznych materiału badawczego. Otrzymane wyniki opracowałam pod względem statystycznym i merytorycznym, przygotowując manuskrypt oraz wizualizację wyników, a następnie uczestniczyłam we współredagowaniu tekstu w procesie recenzji.

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Potwierdzam treść oświadczenia.

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Oświadczam, że w pracy *Marczak D., Lejcuś K., Grzybowska-Pietras J., Biniaś W., Lejcuś I., Misiewicz J. 2020. Biodegradation of sustainable nonwovens used in water absorbing geocomposites supporting plants vegetation. Sustainable Materials and Technologies. 26, e00235. DOI:10.1016/j.susmat.2020.e00235,* mój udział polegał na współtworzeniu koncepcji badawczej i planu publikacji. Współredagowałem manuskrypt pod względem merytorycznym oraz pełniłem rolę autora korespondencyjnego w procesie publikacji.

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

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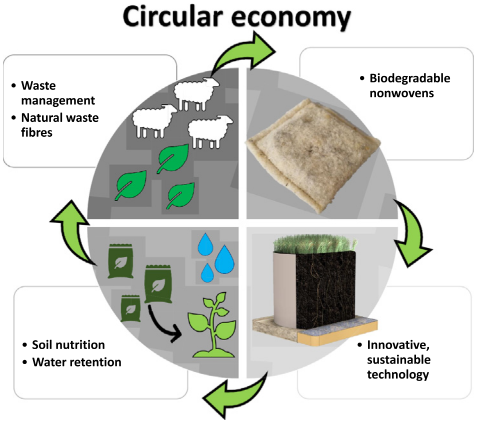
HIGHLIGHTS

- 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



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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

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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).

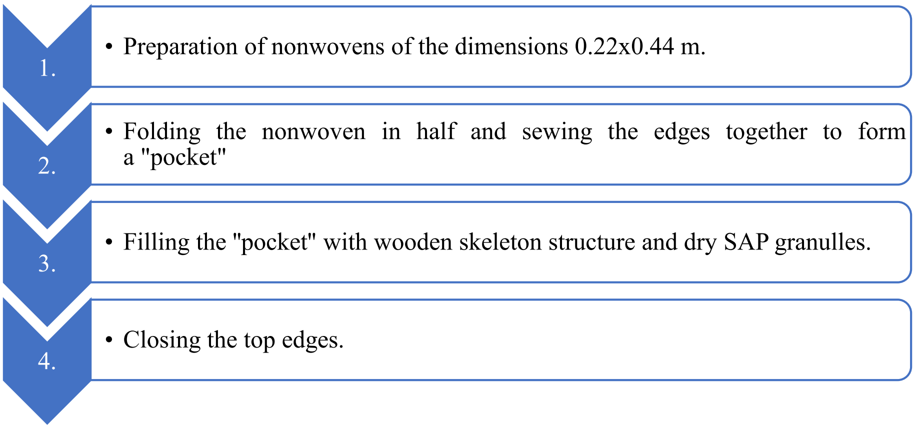
2.2.3. Course of the experiment

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.

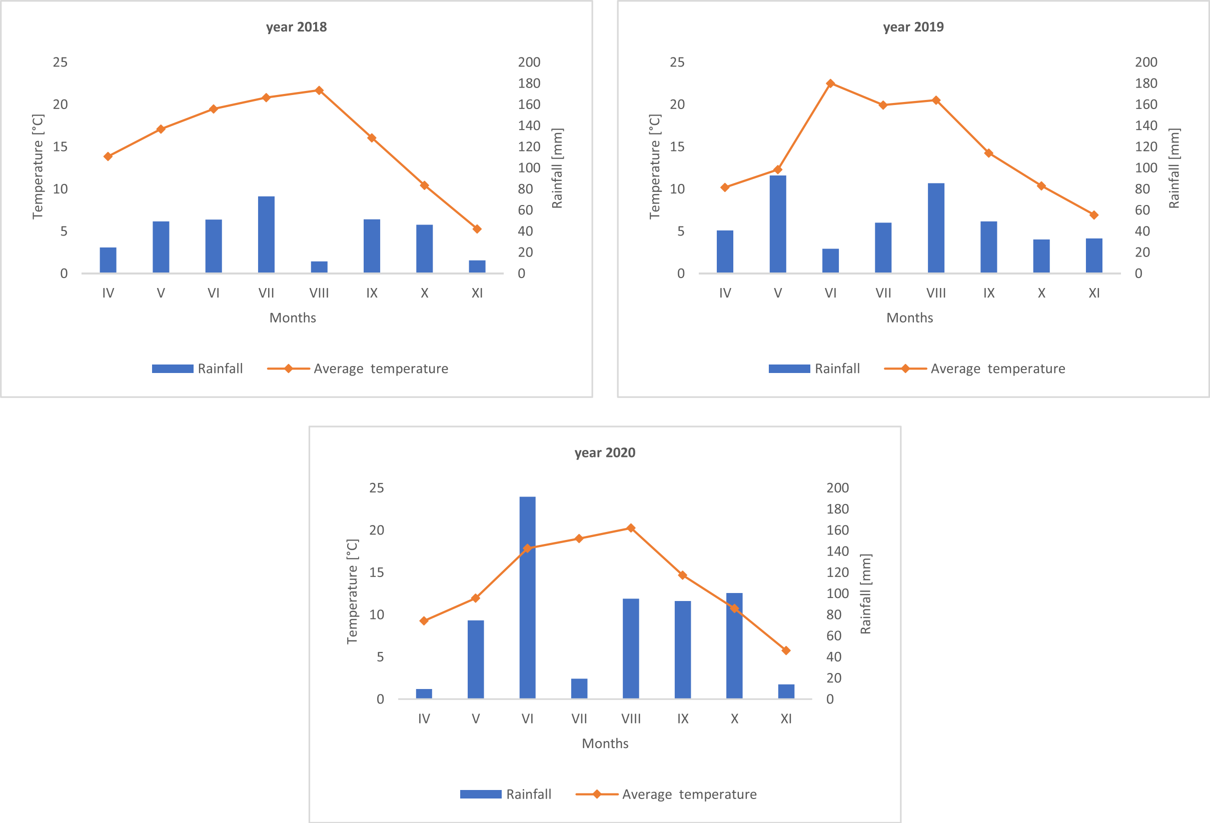


Fig. 3. Average monthly temperatures and total rainfall noted in the years 2018–2020.

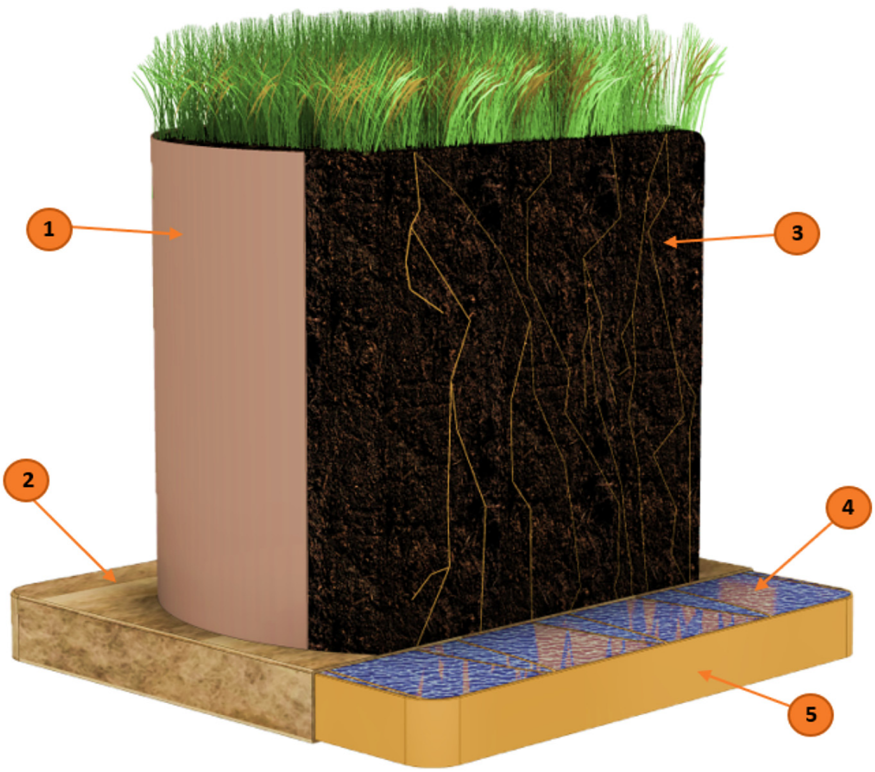


Fig. 4. Layout of the test site: 1-synthetic cover; 2-nonwoven; 3-soil; 4-superabsorbent (SAP); 5-internal structure.

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 teabag 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)	$\mathrm{RLD} = \frac{L_T}{\mathrm{V}}$	$\left[\frac{m}{m^3}\right]$	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]

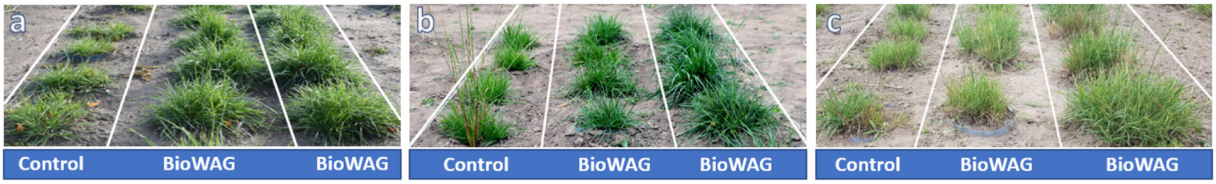


Fig. 5. Condition of the test sites in the years: a-2018, b-2019, c-2020.

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/m^3]	RLD [m/m^3]
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,

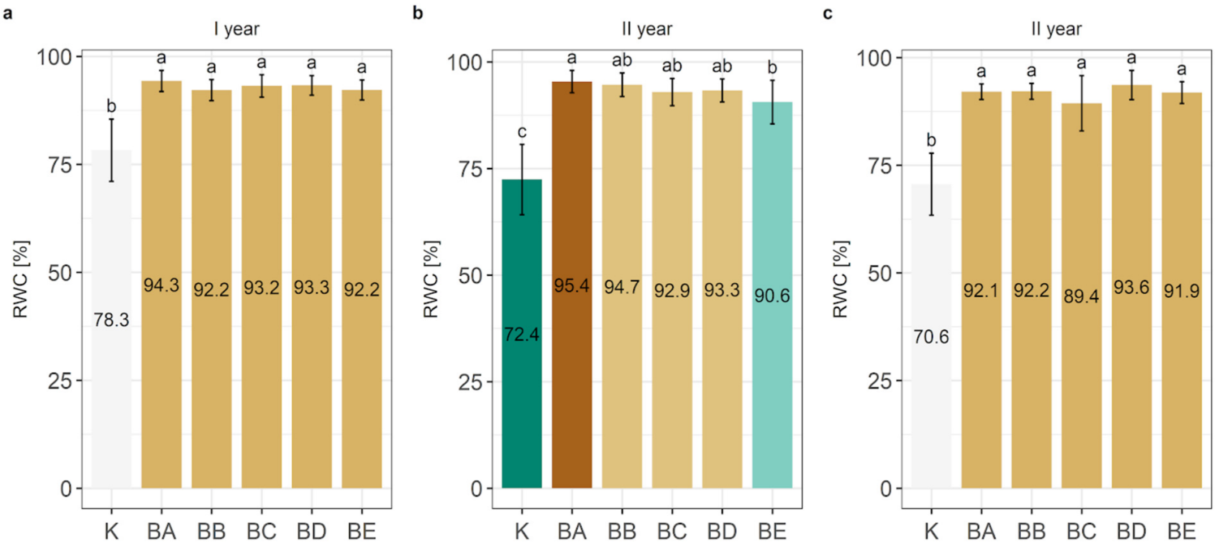


Fig. 7. Average values of the RWC indicator in the years 2018–2020. Error bars indicate the standard deviation (SD); Values indicated by the same letter are not significantly different (a = 0.05).

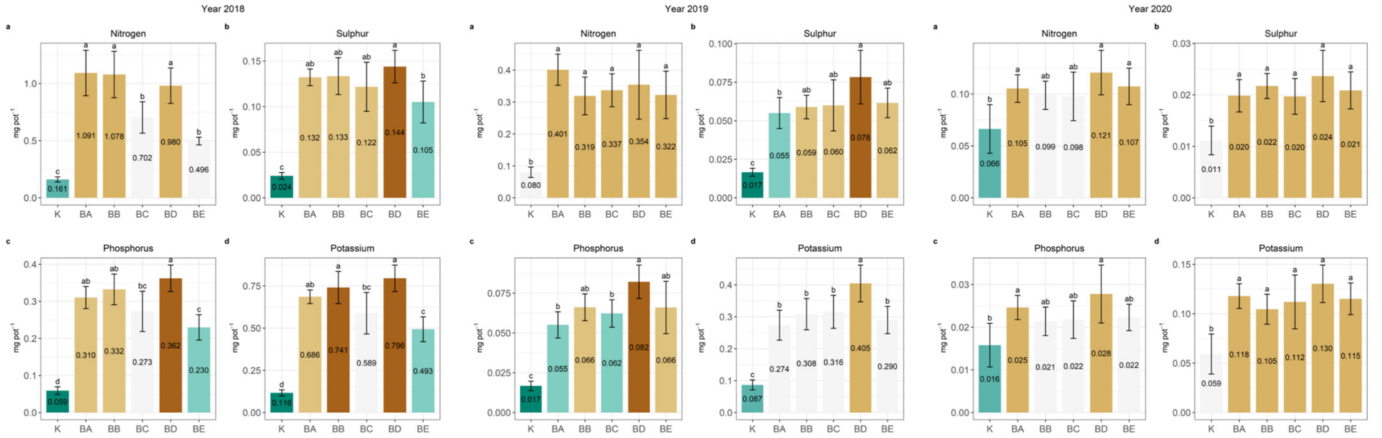


Fig. 8. Uptake of selected macronutrients by plants in the years 2018–2020. Error bars indicate the standard deviation (SD); Values indicated by the same letter are not significantly different (a = 0.05).

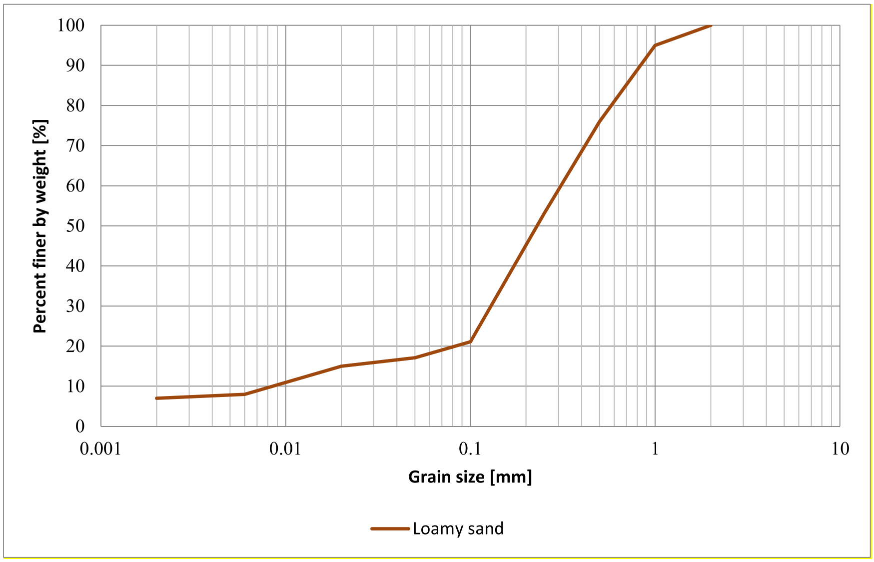


Fig. 9. Particle size distribution of soil used in the experiment.

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] (Špitalniak et al., 2021)	123.00
Cation Exchange Capacity (CEC) [cmol(+)/kg] (Špitalniak 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

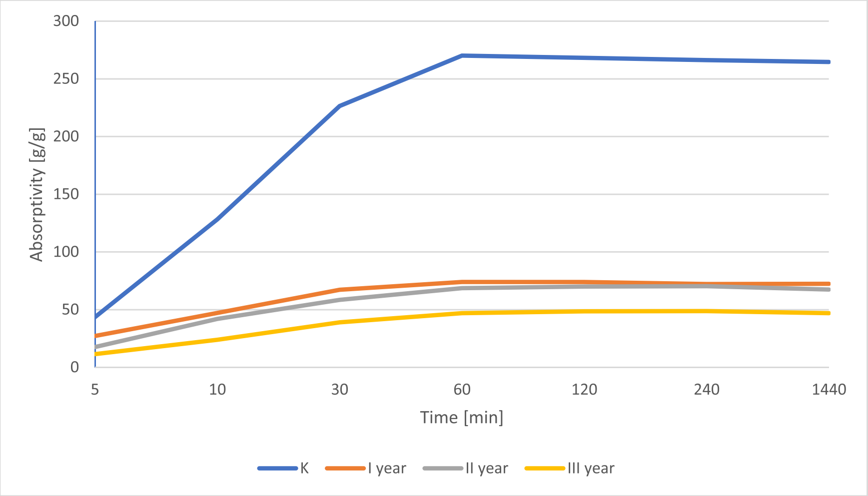


Fig. 10. SAP absorption in distilled water (20 °C).

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


BEFORE BIODEGRADATION
AFTER BIODEGRADATION

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.

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Załącznik nr 3 do Trybu postępowania w sprawie nadania stopnia naukowego doktora

Daria Marczak
imię i nazwisko

Wrocław, 04.09.23r.
miejscowość i data

Instytut Inżynierii Środowiska
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OŚWIADCZENIE

Oświadczam, że w pracy ***Marczak D.,*** *Lejcuś, K., Kulczycki, G., Misiewicz, J. 2022. Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility. Science of the Total Environment. 844, 157169. DOI:10.1016/j.scitotenv.2022.157169,* mój udział polegał na zaproponowaniu i tworzeniu koncepcji oraz planu badań, sporządzeniu przeglądu literatury, przygotowaniu materiału badawczego, przygotowaniu biodegradowalnych geokompozytów sorbujących wodę, założeniu doświadczenia w warunkach rzeczywistych, doborze metodyki badań, określeniu wpływu geokompozytów na wegetację, określeniu zdolności sorpcyjnych SAP. Otrzymane wyniki opracowałam pod względem statystycznym, i merytorycznym, przygotowując manuskrypt oraz wizualizację wyników, a następnie uczestniczyłam w redagowaniu tekstu w procesie recenzji i opracowaniu ostatecznej wersji publikacji.

Byłam wykonawcą w projekcie pt. Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin (nr POIR.04.01.04-00-0061/16; Narodowe Centrum Badań i Rozwoju), obejmującym badania zaprezentowane w niniejszej pracy.

04.09.23r. Daria Marczak
data i podpis

Potwierdzam treść oświadczenia.

04.09.23
data i podpis promotora

Krzysztof Lejcuś
imię i nazwisko

Wrocław, 04.09.23r.
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OŚWIADCZENIE

Oświadczam, że w pracy *Marczak D., Lejcuś, K., Kulczycki, G., Misiewicz, J. 2022. Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility. Science of the Total Environment. 844, 157169. DOI:10.1016/j.scitotenv.2022.157169,* mój udział polegał na współtworzeniu koncepcji badawczej i planu publikacji. Współredagowałem manuskrypt pod względem merytorycznym oraz pełniłem rolę autora korespondencyjnego w procesie publikacji.

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OŚWIADCZENIE

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Jakub Misiewicz
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OŚWIADCZENIE

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Sustainable Innovation: Turning Waste into Soil Additives

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Abstract: In recent years, a dynamic increase in environmental pollution with textile waste has been observed. Natural textile waste has great potential for environmental applications. This work identifies potential ways of sustainably managing natural textile waste, which is problematic waste from sheep farming or the cultivation of fibrous plants. On the basis of textile waste, an innovative technology was developed to support water saving and plant vegetation- biodegradable water-absorbing geocomposites (BioWAGs). The major objective of this study was to determine BioWAG effectiveness under field conditions. The paper analyses the effect of BioWAGs on the increments in fresh and dry matter, the development of the root system, and the relative water content (RWC) of selected grass species. The conducted research confirmed the high efficiency of the developed technology. The BioWAGs increased the fresh mass of grass shoots by 230-420% and the root system by 130-200% compared with the control group. The study proved that BioWAGs are a highly effective technology that supports plant vegetation and saves water. Thanks to the reuse of waste materials, the developed technology is compatible with the assumptions of the circular economy and the goals of sustainable development.

Keywords: circular bioeconomy; sustainable technology; waste management; biodegradation; natural fibres

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1. Introduction

The continuous modifications in the environment caused by human economic activity often lead to the irreversible deterioration of the milieu, posing potential human health and ecological risks [1–5]. The ecosystem is facing numerous types of environmental pressure, including, among others, climate change, water deficits, and soil degradation, along with the increasing need to provide food and water safety for the growing population [6–9]. As a result, water access and fertile soil access are indispensable elements of the sustainable development of today's world and are at the same time very difficult to achieve and maintain for a long period. According to analyses, failure to introduce sustainable solutions in water management and soil protection will lead to severe threats for human health and environment quality [10–14]. This has resulted in a growing interest in various types of soil additives that improve the retention capacity and fertility of soils.

As far as water retention is concerned, popular soil additives include, among others, zeolite, attapulgite, and superabsorbents (SAPs), which effectively reduce the consumption of water for irrigation and mitigate the effects of droughts [15–20]. Regarding the improvement in soil fertility, a wide range of fertilizers that guarantee obtaining the appropriate quality of crops in a short time and improve production are available [21,22]. According to statistics, the consumption of chemical fertilizers was 198 million t in the world, including 100 million t of nitrogen fertilizers (2016) [23]. Unfortunately, they have some disadvantages, and above of all, they have a negative impact on the environment [24–26]. The main problem caused by the excessive long-term use of soil additives, especially in the context of artificial fertilizers, is the deterioration of soil fertility, and quality and amount of crops, and even soil degradation and loss of biodiversity [27–31]. Another type of soil additives that have become particularly popular in recent years in environmental and hydraulic engineering are geotextiles. They may perform mechanical, hydraulic, and biological functions if applied to engineering objects [32–35]. They work very well in agriculture and horticulture as retention-enhancing materials and natural fertilizers [36,37]. Unfortunately, although they have numerous advantages, they pose a significant burden for the environment, particularly because a vast majority of them is produced using synthetic fibres [38–40]. The textile industry generated almost 2 million tonnes of CO_2 (2015) and consumed approximately 80 billion cubic meters of water, which indicate a pollution level that threatens the life of humans and animals [41–44]. At the same time, one should bear in mind that plastics stored in soil may release complex mixtures of chemical substances into the environment and that their hydrophobic surface allows them to adsorb and store high concentrations of organic pollutants and heavy metals [45]. Global plastic production reached 3.68 billion tons in 2019. It is estimated that the upward trend will continue until 2050; thus, the global production of plastics may increase to 25 billion tons [46]. Once released into the environment, these materials are prone to degrade, generating microplastics and nanoplastics, which can cause a broad range of toxicological effects on animals and humans [46–48]. Moreover, a rapid increase in the production of plastic waste, which is mainly due to the short period of plastic use, has been noted in the last decade [49]. According to estimations, the life of approximately 40% of plastic products does not exceed one month, and materials used in agriculture, horticulture, and environmental engineering are rarely used for a period longer than one or two vegetation seasons [37,50]. As a result, it is desirable to seek and apply alternative solutions that take into account the current environmental challenges.

Responsible production with the use of biodegradable materials is crucial in reducing the consumption of fossil fuels, greenhouse-gas emissions, and the storage of plastics in landfills [49]. The application of materials that undergo gradual biodegradation in soil offers a promising outlook [51–54]. The choice of biodegradable materials is particularly advisable in short-term solutions [55–58]. When applied to soil, they improve its mechanical properties, and as a result of biodegradation, they release compounds promoting vegetation [59–62]. In most cases, the choice of natural fibres such as wool, jute, or linen for manufacturing geotextiles is also reasonable from the economic point of view [63–66]. These materials are usually by-products of breeding sheep, cultivating fibre plants, or manufacturing textiles in the clothing industry. Currently, attempts at applying natural fibres in environmental engineering and agriculture, where they act as elements that support plant growth and provide anti-erosion protection to civil engineering structures, are being made [36,64,67]. This subject has not been thoroughly analysed yet; the available materials are not always effective, and the conducted research focuses on a narrow range of applications. As a result, there is clearly a need to use the potential of such materials and to develop technologies that meet the current needs of the market while taking into account the sustainable development goals and the objectives of circular economy, such as improving the efficiency of water management and soil fertility, reducing the amount of waste, and limiting soil degradation.

Biodegradable water-absorbing geocomposites (BioWAGs) have been developed to solve the problems discussed above. This technology has a three-dimensional form that retains water in the form of gel so that it is available for plants. A BioWAG consists of three main elements: biotextile, which separates the whole structure from the soil; a superabsorbent polymer, which absorbs water and its solutions; and an internal skeleton structure, which provides space for free water absorption [68,69]. The plant root system can freely grow into the WAG interior and take up the water stored in the SAP [70]. The geocomposite water storage process is very efficient and can take place many times [68]. WAGs can be manufactured both in a durable version (WAGs) based on synthetic materials and in a biodegradable version (BioWAGs). The use of geocomposites has a positive effect on the development of the plant root system, increasing the erosion resistance of engineering structures, such as flood embankments. This technology also reduces evaporation from the soil and improves the biometric parameters of plants [68,71–74].

This work illustrates the need for a sustainable approach to natural resources and indicates the possibility of using waste materials in a closed cycle. This paper presents a new, sustainable approach to the management of textile waste materials to reduce environmental pollution, recover valuable nutrients readily available to plants, and reduce the water consumption necessary for irrigation. We explored the possibilities of biodegradable waste management using innovative technology in the form of BioWAGs. The research presented was conducted under actual field conditions so as to take into consideration the influence of external factors. The major purpose of the work was to determine the potential of textile waste materials for the production of an innovative technology to support plant vegetation and save water in the form of BioWAGs and to determine BioWAG effectiveness under field conditions. We analysed the effect of BioWAGs on the increments in fresh and dry matter, the development of the root system, and the relative water content (RWC) of selected grass species.

2. Materials and Methods

2.1. Site Characteristics

The experiment was carried out at Agricultural and Hydrological Observatory Wrocław-Swojec (51°07′ N, 17°10′ E), Wroclaw University of Environmental and Life Sciences, Poland, located in the northeastern area of the city. The duration of the experiment was from May to October. Wrocław is located in SW Poland, in the moderate climate zone. The annual precipitation in Lower Silesia is between 560 and 600 mm [37,75].

2.2. Climatic Conditions

The average daily temperatures in the test period ranged from 5.1 to 25.9 °C (May–October 2018). Total monthly precipitation ranged from 11.4 mm in August to 72.9 mm in July (Figure 1). During the test period, 38 days with rainfall exceeding 1.0 mm were noted. The highest total monthly precipitation (72.9 mm) was observed in July, and the lowest one, in August (11.4 mm). During the test period, the average temperature was 16.6 °C, which exceeds the long-term average (1971–2000) by 1.7 °C. The total rainfall was 282.1 mm, which is 86.8 mm lower than the average annual rainfall (1971–2000) [37,76].

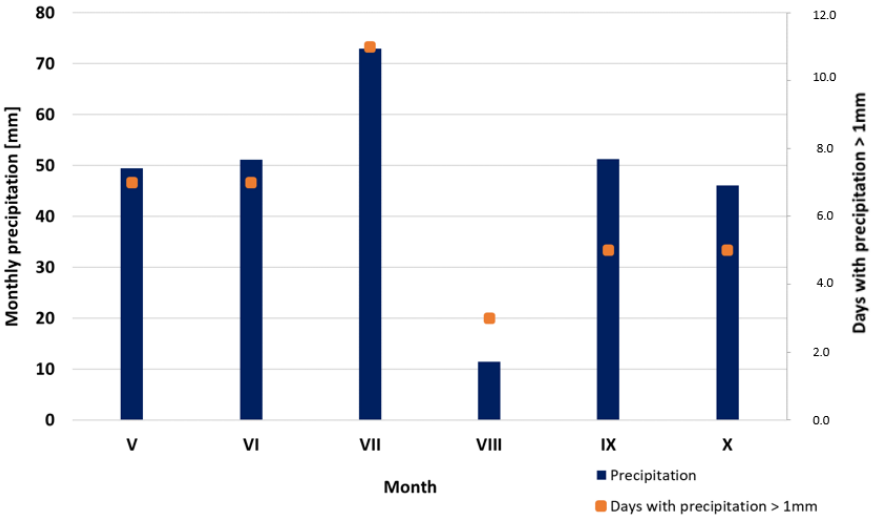


Figure 1. Histogram of total precipitation by month in the analysed period. Meteorological data were obtained from Faculty Agricultural and Hydrological Observatory Wrocław-Swojec (WOAiHW-S).

2.3. Materials

The tests were conducted with the use of prototype BioWAGs prepared in the form of mats with spatial dimensions of 0.22 × 0.22 × 0.22 m. The WAG prototypes consisted of Aquasorb 3005 KL superabsorbent polymer (SNF FLOERGER, Andrézieux, France); a wooden skeletal structure (0.20 × 0.20 × 0.02 m); and a biodegradable nonwoven, which constituted the sheath (Table 1). The used superabsorbent polymer is a cross-linked copolymer of acrylamides and potassium acrylate that undergoes gradual biodegradation under the influence of environmental factors, including selected soil bacteria [70]. Bacteria causing slow SAP degradation include *Variovorax boronicumulans*, *Enterococcus faecalis*, *Klebsiella pneumoniae*, and *Geobacillus thermoglucosidasius* [77,78]. All nonwovens used in the production of the WAGs were analysed based on their physical and mechanical properties before and after biodegradation (after one vegetation season). The surface masses of the scoured nonwovens were BA, 368 $g \cdot m^{-2}$; BB, 287 $g \cdot m^{-2}$; BC, 333 $g \cdot m^{-2}$; BD, 289 $g \cdot m^{-2}$; and BE, 308 $g \cdot m^{-2}$. The detailed results concerning the parameters of nonwovens before and after biodegradation were published in the paper by Marczak et al. [37].

Table 1. Attributes of the analysed materials.

Sample Name	Composition of Raw Materials and Manufacturing Technology	Sample Photo
BA	99.4% washed wool and 0.6% synthetic seams; seamed textile	
BB	100% washed wool; needle-punched nonwoven	
BC	90% washed wools and 10% jute; needle-punched nonwoven	
BD	90% washed wool and 10% jute; seamed textile	
BE	50% washed wool and 50% linen; needle-punched nonwoven	

2.4. Preparation of BioWAG Prototypes and Test Sites

The prototypes of the BioWAGs were prepared using rectangular fragments of nonwovens (0.44 × 0.22 m), which were folded and sewn with cotton thread to create square mats of the dimensions of 0.22 × 0.22 m. A wooden skeletal structure and the SAP in the form of dry granules ranging from 0.50 mm to 2.00 mm were placed inside the mat, which was then sewn shut. The dose of the SAP was selected so that after swelling, the SAP could fill the free space inside the geocomposite. The WAGs prepared in such a way were soaked in water before application in soil and then placed at the bottom of a hole with the diameter of 0.30 m prepared on the test field. The walls of the hole were additionally protected with a synthetic sheath to ensure the same area for the development of the plant root system at all sites. The applied geocomposites were covered with a layer of humus (of the grain size distribution of loamy sand) with a thickness of approx. 0.15 m. The used soil was classified according to the United States Department of Agriculture (USDA) classification [79]. The study determined the basic parameters of the soil, such as pH 6.20 1 $M \cdot dm^{-3}$ KCl, specific weight of 2.65 $g \cdot cm^{-3}$, bulk density of 1.65 $g \cdot cm^{-3}$, and soil organic matter (SOM) of 2.93%. Detailed soil parameters are presented in more detail in the article [69]. All sites were sown with 0.63 g of grass mixture seeds (which corresponds to 200 $kg \cdot ha^{-1}$) [37].

2.5. Description of the Experiment

The tests were conducted from May to October 2018. Each type of BioWAG and the control site were installed in 9 iterations. Samples were placed at random, so as to eliminate the influence of threshold conditions. All sites were regularly irrigated until grass sprouted and rooted (approx. 2–3 weeks after sowing). The same doses of irrigation were used at each site in order to ensure comparable vegetation conditions. After that time, no additional irrigation was conducted until the end of the vegetation season, so the amount of water stored in the BioWAGs depended on atmospheric conditions. The condition and growth of plants were regularly monitored by controlling fresh and dry weight, and the water balance of plants. In order to assess the root systems of plants, after the end of the vegetation season, roots, protected with plastic sheaths, were collected from the test sites (surface area: 0.0314 m^2; height: 0.20 m). Samples were additionally protected with foil and transported to the laboratory in intact condition. After taking photographs for documentation and collecting the BioWAGs for further analyses, the root mass was soaked in water to remove soil particles (Figure 2). The cleaned root systems of grass were subjected to biometric analyses.

Figure 2. Preparation of the sample for laboratory tests.

2.6. Research Methodology

2.6.1. Measuring the Fresh and Dry Weight of Plants

Grass coverage at test sites was regularly monitored during the analysed period. Fresh weight and dry weight were measured regularly, every 7–8 weeks. During the analysed season, swaths were conducted 3 times, and measurements were taken in 9 iterations. All sites had the same surface area (0.0314 m^2) defined by the plastic sheath installed in soil. Grass was manually cut, with shears, as close to the ground as possible. The cut growth was placed in a plastic bag and weighed after transporting to the laboratory. In order to obtain the dry weight, the grass was laid out in a laboratory drier with natural air circulation at the temperature of 70 °C and dried until a fixed weight of samples was obtained (48 h) [80].

2.6.2. Relative Water Content (RWC) Measurement

The degree of plant hydration was assessed based on the relative water content (RWC). RWC was measured during each analysis of the dry and fresh weight of plants. Samples of grass blades collected from the field were placed in string bags and transported to the laboratory. In order to determine the RWC, we measured fresh weight (directly after collecting the grass blades), turgid weight (obtained after soaking the leaves in deionised water for 24 h), and dry weight (after drying in a laboratory dryer with natural air circulation, at the temperature of 70 °C, until a fixed sample weight was obtained). The RWC values were calculated using the following (Equation (1)) [80,81]:

$$\mathrm{RWC} = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}} \cdot 100 \tag{1}$$

where RWC is the relative water content (%), FW is the fresh weight (g), DW is the dry weight (g), and TW is the turgid weight (g).

2.6.3. Analysis of the Development of Plant Root System

The root monoliths of plants were collected from the experimental field in November, after the growing season had passed. The measurements were taken in 9 iterations for each type of WAG and the control group. The condition and development of the root system were analysed with the use of biometric measurements. The roots were dried in a laboratory dryer with natural air circulation, at the temperature of 70 °C, and dried until a fixed weight of samples was obtained (48 h). Then, their dry weight was measured. The length and total density of the root system were also measured. The total density was calculated with the following (Equation (2)):

$$\rho = \frac{m}{V} \tag{2}$$

where ρ is the density ($\mathrm{g \cdot m^{-3}}$), m is the dry weight (g), and V is the volume of soil from which the root system was collected ($\mathrm{m^3}$).

The monolith method was used to determine the depth distribution of the RLD [82,83]. The obtained measurements of root length and the known volume of soil were the basis for the determination of the root length density (RLD) index (3).

$$\mathrm{RLD} = \frac{L_T}{\mathrm{V}} \tag{3}$$

where RLD is the volume density of the root system ($\mathrm{m \cdot m^{-3}}$) $\mathrm{L_T}$ is the total length of the roots (m), and V is the volume of the soil from which the root system was collected ($\mathrm{m^3}$).

Then, the root system was divided into 0.05 m wide belts, and the dry weight of roots in specific layers and the designated density of roots in the 0.05 m thick layer were measured using the following (Equation (4)):

$$\rho_{0.05m} = \frac{m_{0.05m}}{V_{0.05m}} \tag{4}$$

where $\rho_{0.05m}$ is the density determined in the 0.05 m thick layer ($\mathrm{g \cdot m^{-3}}$), $m_{0.05m}$ is the dry weight determined in the 0.05 m thick layer (g), and $V_{0.05m}$ is the volume of the soil determined in the 0.05 m thick layer ($\mathrm{m^3}$).

2.7. Data Analysis

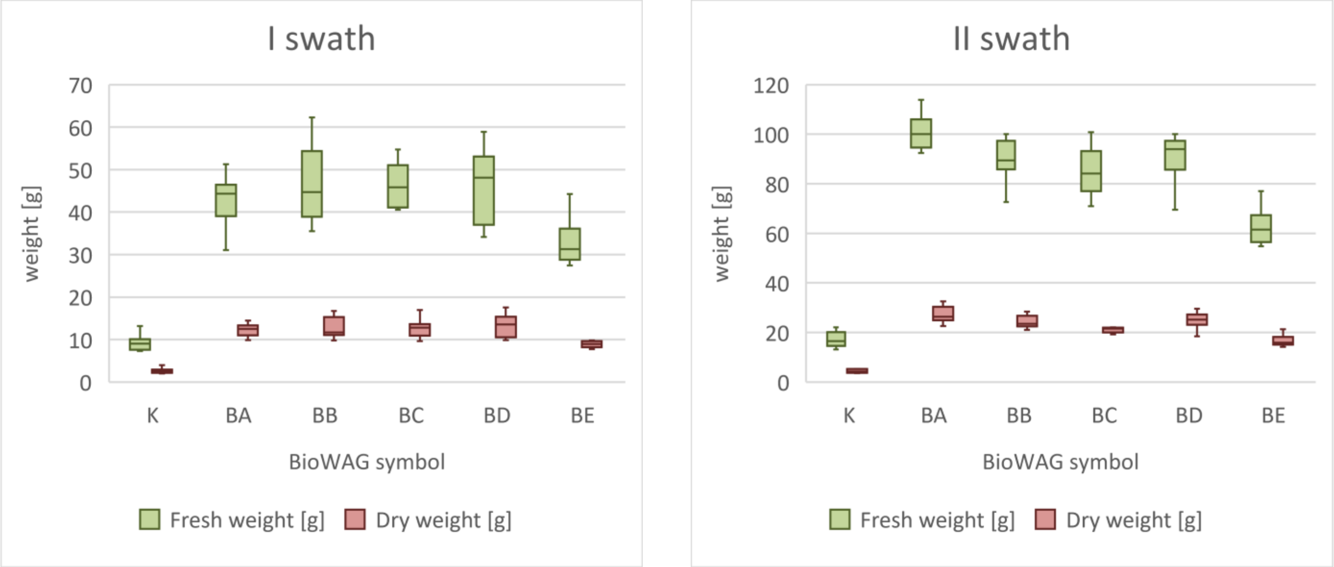
The study was carried out in a randomized system so as to eliminate the possible impact of environmental factors. Boxplot analysis was used to observe the data range and identify any invalid data. Boxplots show the data distribution, range, minimum and maximum range values, lower quartile, upper quartile, and median [84,85]. Statistics for all the boxplots were prepared using Excel v 2019.

3. Results

3.1. Plant Growth

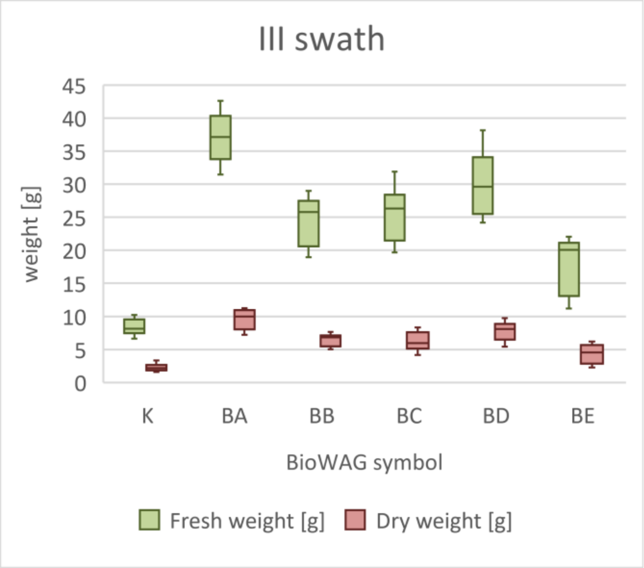
The tests revealed that BioWAGs had a positive influence on all the analysed biometric properties of plants. Several weeks after sowing, the sites were covered with grass. The grass growing in sites where BioWAGs had been applied was in a much better condition than that in the control sites. The plants had an intense green colour and were higher, and the grass cover was much denser and more cohesive.

Throughout the vegetation season, the increase in the fresh and dry weight of grass that was noted in sites with BioWAGs was higher than that in control sites (Figure 3). As early as after the first swath, the increase in the fresh weight of grass from sites with WAGs was, on the average, from 264 to 410% higher. Regarding the dry weight, the increase was 241 to 377% higher. At the same time, the highest effectiveness for both the fresh and dry weight of plants was noted in sites marked with the BD symbol. The highest effectiveness of WAGs in the whole season was noted after the second swath. The increase in the fresh weight of grass from test sites was 267 to 490% higher, and the increase in dry weight, from 248 to 467% higher. This time, the best results were observed in sites marked with the BA symbol, which resulted from the intensified biodegradation process of the material and the releasing of N and K into the soil. The increase after the third swath was 110 to 344% higher for fresh weight and 95 to 325% higher for dry weight. The best effects were noted, once again, in the sites marked with the BA symbol.



(**a**) (**b**)

Figure 3. *Cont.*



(**c**)

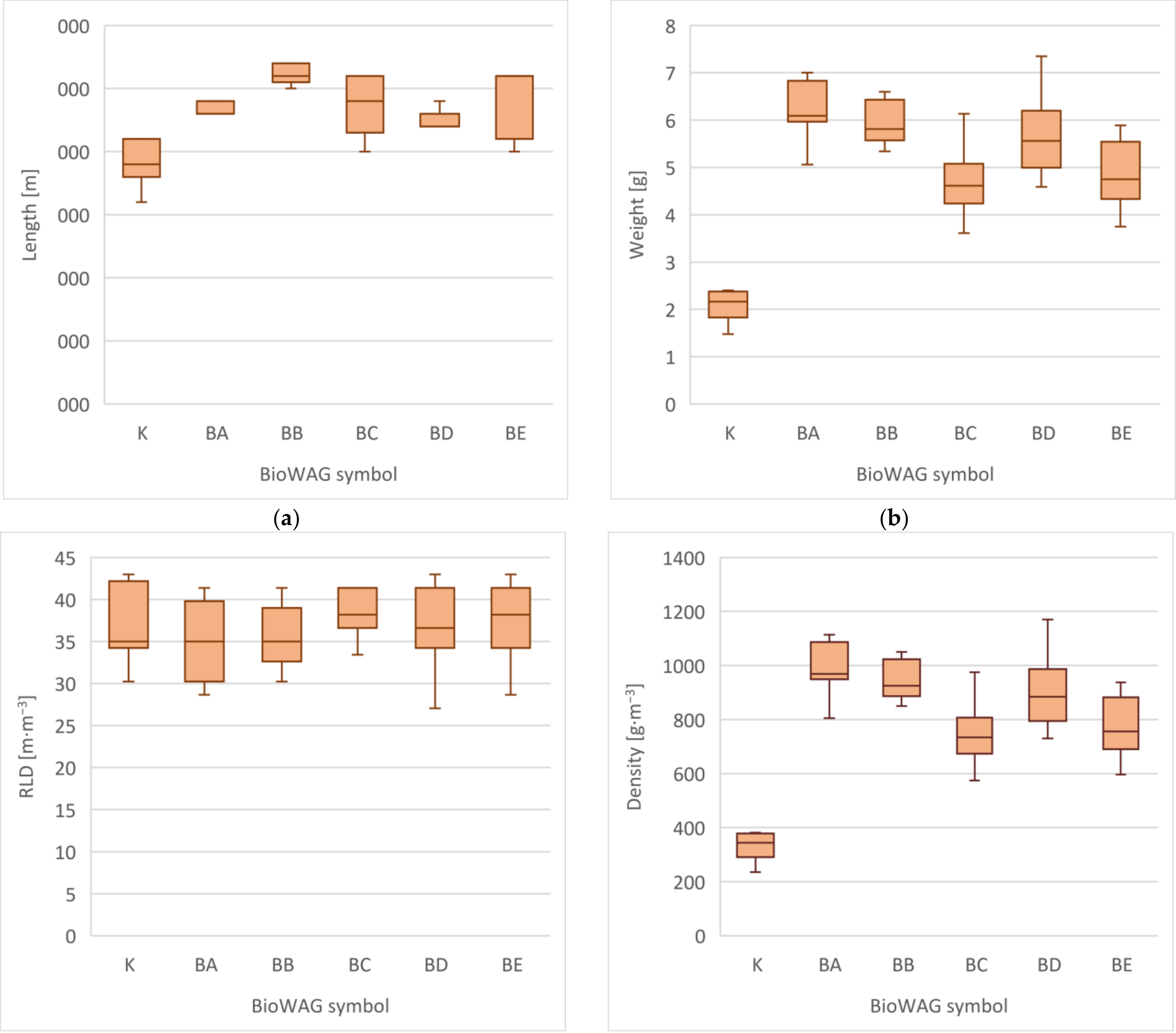
Figure 3. Influence of BioWAGs on the growth of above-ground biomass and dry above-ground mass. (**a**) Growth of fresh and dry grass after the first swath, (**b**) growth of fresh and dry grass after the second swath, and (**c**) growth of fresh and dry grass after the third swath. The diagrams show the first and third quartiles, medians, and minimum and maximum values.

The highest effectiveness of BioWAGs noted after the second swath was directly linked to the atmospheric conditions in the period preceding the swath. August was the month with the lowest total precipitation and the highest average temperature in the whole analysed period. At that time, the plants had already a well-developed root system, which, thanks to hydrotropism, was able to quickly reach the water retained in the geocomposite. After the plants had grown through it, single granules of the SAP were distributed along the roots, providing the plant with continuous access to water. Depending on the material used, the biodegradation process of the elements of the BioWAGs started or intensified. Plants in sites where BioWAG was applied were provided with a sufficient amount of water and nutrients in that period, regardless of the environmental and climate conditions, which undoubtedly contributed to intensified growth.

3.2. Root Growth

The root systems of grass in sites with BioWAGs were dense and resistant structures that grew through the whole space of the geocomposite. In order to determine the efficiency of the WAGs at the end of the growing season, selected parameters of the root system were analysed, i.e., total length, total weight, weight at various depths, the RLD index, and density (total density and density at various depths). The analysis of these parameters revealed the favourable influence of the WAGs on the increase in and development of the root system (Figure 4). The application of BioWAGs caused increases in the length and in the RLD index of 24% (BA), 36% (BB), 25% (BC), 18% (BD), and 26% (BE) in comparison with the control group. The smallest differences were observed in BD sites and resulted from the low degree of biodegradation of this geocomposite. The remaining sites were subjected to more intense biodegradation, which created the possibility to collect them in an intact state from deeper levels. A detailed description of the progress in the biodegradation of the BioWAGs used in the research was presented in the paper by Marczak et al. [37].

Similarly, the dry weight and density of the root system were higher in sites where the BioWAGs had been applied. The application of this technology resulted in increases in biomass and root density of 202% (BA), 194% (BB), 125% (BC), 171% (BD), and 134% (BE) in comparison with the control block. In these cases, the best results were obtained in sites that were subjected to intensive biodegradation, at the same time improving the composition and fertility of the soil.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. Biometric measurements of grass root system noted after the vegetation season (2018), depending on the type of BioWAG used: (**a**) length of the root system; (**b**) total weight of the root system; (**c**) values of the RLD index measured in reference to the total length of the root system; (**d**) total density of the root system. The diagrams show the first and third quartiles, medians, and minimum and maximum values.

The analysis of the development of the grass root system in 5 cm thick layers allowed us to determine that the application of WAGs fostered creating a greater volume of roots in all the analysed depth ranges than in the control group. The root system was best developed in the 0.00–0.05 m range, where its density was 171% (BC) to 264% (BA) higher. In the 0.05–0.10 m and 0.10–0.15 m ranges, this parameter was 70% (BC) to 128% (BA) higher. The largest differences were observed in the 0.20–0.25 m range, where the root system density was 238% (BE) to even 688% higher (BA). Such large differences resulted from the lower reach of roots in control sites.

3.3. Relative Water Content (RWC) Measurement

The conducted analyses revealed a positive influence of the BioWAGs on the relative water content in grass leaves. During the whole vegetation season, the RWC in the test sites was approx. 10% to 35% higher than that in control sites (Figure 5). The best results were noted in samples collected after the second swath, which was directly linked to the disadvantageous atmospheric conditions in the period preceding the swath. August was the month with the lowest total precipitation and the highest average air temperature. As a result, plants in control sites were exposed to water stress. Regarding sites with BioWAGs, the RWC parameter did not fall below 91%, regardless of the type of applied water-absorbing geocomposite and the atmospheric conditions.

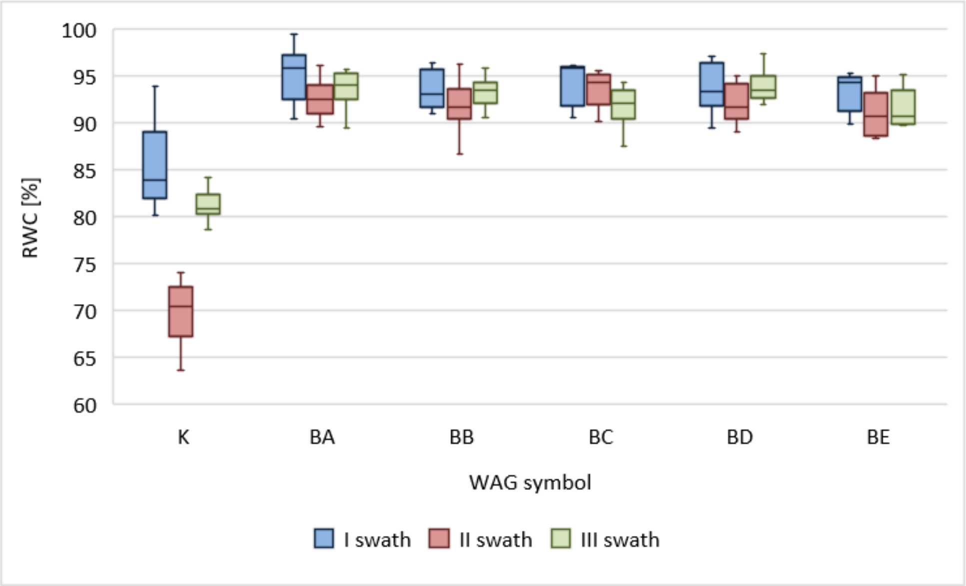


Figure 5. The influence of WAGs on relative water content (RWC). The diagram shows the first and third quartiles, medians, and minimum and maximum values.

4. Discussion

The article presents the results of our research on the impact of biodegradable water-absorbing geocomposites on plant vegetation. The combination of the sorption capacity of the superabsorbent polymer and the biodegradable materials that are rich in nutrients allowed us to develop an innovative technology to save water and support plant growth. The results here presented demonstrate that this solution is highly efficient. The application of BioWAGs guarantees continuous access to water regardless of the atmospheric conditions. Moreover, it increases the growth of plants, mitigates the effects of water stress, and as a result, limits fertilizer use and reduces the negative environmental impact.

4.1. Relative Water Content (RWC)

Some of the effects of water deficit include diminished crops and limited development of plants. Numerous authors have confirmed that even mild stress caused by drought may lead to significant modifications in the physiological and chemical processes of plants. The yield of grass is closely linked to soil moisture content, i.e., grass responds to increased water content in the soil by significantly increasing the yield [86]. The results presented in this study confirm this phenomenon. The sites with BioWAG application provided plants with continuous access to water, which increased the crops by 270 up to 490% and reduced the stress caused by water deficit. The highest differences were noted under unfavourable weather conditions, when the plants were exposed to water stress. During that time, a noticeable decrease in growth in the control sites was noted. The literature reveals that droughts in Poland may cause a decrease in the yield of grass of approximately 30% [87]. Research by Staniak [88] indicated that the stress caused by water deficit led to a reduction in the dry weight of grass of approx. 31% in comparison with sites with optimum water content. In comparison with traditional irrigation, the application of BioWAGs ensures multiple times higher effectiveness, while at the same time, it makes it possible to save water and protect the environment. The optimum hydration of plants was also confirmed by higher values of the RWC index (91–95%), which were noted throughout the season in sites with BioWAGs in comparison with the control sites (69–85%).

4.2. Plant Growth

In recent years, superabsorbent polymers (SAPs) have been successfully used as soil additives, providing a reserve of water and of certain nutrients. These materials are an efficient tool for reducing the results of water stress, and they have a positive influence on plants cultivated in agriculture, horticulture, and environmental engineering [16,89,90]. However, in field applications, they have certain disadvantages that significantly limit their effectiveness. The main disadvantage is the reduced absorption capacity of SAPs under loading [79]. As far as WAGs are concerned, this weakness has been eliminated thanks to introducing the internal skeletal structure that ensures the free space required by the SAPs to properly swell. Lejcuś et al. [68] analysed the effectiveness of synthetic water-absorbing geocomposites in field applications. The non-biodegradable version of geocomposites had a positive influence on the biometric parameters of the turf overgrowing the slopes of the test embankment. The application of geocomposites resulted in an increase in the root volume of 130% and an in increase in their length of 29%. After the first year of the experiment, the dry weight of the above-ground parts of plants increased by 50%, and the fresh weight, by 58%, in comparison with the control group. The comparison of these results and the new, biodegradable version of WAGs allows us to state that the application of biodegradable materials improves the efficiency of this technology by even 6.5 times, depending on the analysed parameter and the material applied.

Water access and nutrient access are the main determinants of plant growth. Irrigation increases nitrogen availability, while the presence of nitrogen in the soil promotes water use, thus contributing to the growth of plants [91]. The unreasonable use of fertilizers, in particular nitrogen, has been the main threat for many years, both in terms of plant quality and environmental protection [92,93]. Users are continuously searching for alternative solutions, such as biodegradable materials or other natural fertilizers. Such materials include, among others, sheep's wool, whose exceptionally rich composition makes it unique. It contains, among others, nitrogen, phosphorus, and potassium, which are available for plants in an easily accessible form [94,95]. In some of their studies, Broda et al. [96–98] noted a positive influence of waste wool applied to slopes on grass. In the places of application, the grass was much higher; it had a bright green colour and formed a dense, cohesive cover, as opposed to the control sites. Due to the degradation of wool, nitrogen was delivered to the soil, which fostered vegetation. Zheljazkov et al. [99] demonstrated that the process of biodegradation of wool was relatively slow, so it acted similarly to a slow-release fertilizer. The application of wool in a field experiment led to a two–three-fold increase in crops of *Digitalis purpurea* L. in comparison with the control group. Lal et al. also noted an improvement in soil fertility after the application of waste wool, as well as increased contents of organic carbon, nitrogen, and soil enzymes, of approx. 30% in comparison with the control group. The present study confirms the observations of other authors concerning the positive influence of wool on vegetation. In sites BA, BB, BC, and BD, where the percentage of wool was the highest, the growth of the above-ground parts of plants was 50–90% higher than in the BE site, which had the lowest content of wool. The FTIR analysis of the wool samples, which was described in detail in the paper by Marczak et al. [37], established that the biodegradation of keratin protein is accompanied by the release of nutrients that are easily accessible for plants into the soil. A correlation between the degree of biodegradation of the nonwovens and the development of the plant root systems at the depth below 0.20 m was also observed. In sites prepared with the use of needle-punched nonwovens (BB, BC, and BE), the degradation was so advanced that the textiles lost their integrity, and the root system was so well developed that it created a dense, cohesive structure and grew much deeper. This is particularly important when applying BioWAGs to engineering objects, such as flood embankments or road embankment slopes. Plants that grow roots in the layer of humus that is subjected to sliding grow through it, forming a mechanical connection with high resistance to the tearing of roots. The root system reinforces the soil, thus preventing landslides. Although numerous studies on the influence of soil additives on plant vegetation have been conducted, it is rather difficult to provide a straight comparison of the results presented here due to the innovative nature of the described technology. BioWAGs combine the properties of soil additives that improve retention, such as SAPs or zeolite, and fertilizers. Table 2 contains the results of research presented by other authors taking into account the influence on vegetation in terms of both increasing water retention and providing nutrients.

Table 2. Comparison of the influence of soil additives on plant vegetation.

Soil Additive	Plant	Brief Characteristics	Influence on Vegetation	References
- Hydrogel at various concentrations (0%, 0.2%, and 0.4%).	Agrostis stolonifera grass	- Controlled conditions (greenhouse). - Duration: 10 weeks. - Irrigation to ensure full saturation of the substrate with water.	- Increase in the fresh weight of shoots of 60–300% (higher with 0.4% hydrogel). - Increase in the fresh weight of root system of 30–120% (higher with 0.4% hydrogel).	[100]
- a-CSA-Hydrogel, and volcanic rock flour and bentonite. - b-CSA-Hydrogel, and digested fermentation compost and humic acids.	Cat grass (*Dactylis glomerata* L.)	- Field experiment (open-pit mine in Germany). - Duration: 2 years. - No irrigation.	- After 1 year: increase in the fresh weight of shoots of 90% (a-CSA); no differences were noted in the b-CSA site. - After year 1, no influence of additives on the growth of root system was noted. - After year 2, no influence of additives on the growth of above-ground parts was noted. - After year 2: increase in the dry weight of root system of 65% (a-CSA); no differences were noted in the b-CSA site.	[101]
- Sheep manure. - Avikhad. - Dirty waste wool (directly after shearing sheep). - Cleaned waste wool.	Barley	- Field experiment (semi-arid region of Delhi, India). - Duration: 2 years. - No irrigation.	- Increases in the fresh weight of shoots of 12% (waste wool), 16% (wool manure), and 47% (sheep manure). - Increase in crops of 50% (waste wool).	[95]
- Mineral: 100 kg N·ha^{-1} and 30 kg K·ha^{-1}. - Digested: 26.3–30.3 t·ha^{-1} biogas station (mineral N, organic N, P, K, Ca, and Mg).	Tall wheatgrass (Elymus elongatus subsp. ponticus) and reed canary grass (*Phalaris arundinacea* L.)	- Field experiment (Czech Republic). - Duration: 6 years. - No irrigation.	- Increases in the dry weight of tall wheatgrass of 14% and in that of reed canary of 6% (digested). - No significant influence of mineral fertilizer on the increase in dry weight was noted.	[102]
- Various doses of nitrogen fertilizer (330 kg N·ha^{-1}, 270 kg N·ha^{-1}, and 210 kg N·ha^{-1}).	Winter wheat	- Field experiment (North China Plain). - Duration: 3 years. - A total of 1 or 2 doses of irrigation per season.	- The highest increase in dry weight, 5–10%, was noted with the fertilizer dose of 270 kg N/ha.	[103]
- Zeolite (OZ). - Zeolite enriched with K (K-EZ).	Perennial ryegrass (*Lolium perenne* L.)	- Controlled conditions (greenhouse). - Duration: 3 months. - Regular irrigation.	- Increases in the dry weight of shoots of 10% (OZ) and 31% (K-EZ). - Increases in the dry weight of root system of 27% (OZ) and 68% (K-EZ). - No significant influence of additives on RWC was found.	[104]

Based on the referenced data from the subject literature, noticeably better results were obtained with the application of BioWAGs. The technology described in this paper is not only characterised by retention capacity, but thanks to the presence of biodegradable materials, it also acts as a slow-release fertilizer. Regarding the analysed additives that increased retention, the growth of the above-ground parts of plants was high, i.e., from approx. 30% (zeolite) to 300% (0.4% hydrogel). On the other hand, applying fertilizers increased this parameter by 5% (270 kg N·ha^{-1}) to 47% (sheep manure). At the same time, the effectiveness of biodegradable WAGs was nearly 500% higher throughout the vegetation season, regardless of atmospheric conditions. The application of waste materials makes it possible to reduce environmental pollution, and it perfectly fits the principles of sustainable development and circular economy. The combination of superabsorbents and biotextiles, which have been very well known in agriculture, horticulture, and environmental engineering, is a competitive alternative to existing solutions, especially in regions exposed to droughts, degraded areas, and soils with low contents of plant nutrients.

5. Conclusions

Reasonable water consumption, excessive use of fertilizers, and reduction in soil pollution and waste generation are some of the main factors that influence the quality of the environment. So, to confront the current challenges, biodegradable water-absorbing geocomposites were developed as an innovative technology to support water saving and plant vegetation. The article provides an assessment of the potential of BioWAGs in field applications and their influence on plants. The results presented and described in the article allowed us to draw the following conclusions:

- BioWAGs are a highly efficient solution. The application of this sustainable technology guarantees continuous access to water regardless of the atmospheric conditions. Moreover, they increase the fresh and dry weight of plants, mitigate the effects of water stress, and as a result, make it possible to limit fertilizer use and reduce the negative environmental impact.
- Textiles used in BioWAGs can be successfully produced using the widely available fibres of animal and plant origin, such as linen, jute, or wool. As a result of biodegradation, geotextiles based on natural fibres gradually release, into the soil, easily accessible compounds that become natural fertilizers for plants.
- The research results indicate that BioWAGs have a positive effect on the development of above-ground and underground parts of selected grass species. Irrespective of the kind of biotextile applied, BioWAGs increased the fresh weight of grass shoots by 230–420% and the dry weight of roots by 130–200% in comparison with the control group.
- BioWAGs can reduce the effects of water stress, which was confirmed by the RWC results. The optimum hydration of plants was confirmed by the higher values of the RWC index (91–95%) that were noted throughout the season in sites with WAGs.
- The time of effective operation of BioWAGs may be adjusted to the requirements of plants and users' expectations by using textiles with a particular time of biodegradation. All the materials applied in this work showed potential for at least one vegetation season. This time is suitable for the germination and development of plants used to protect slopes (grass and shrubs), ornamental plants, or agricultural crops.

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Załącznik nr 3 do Trybu postępowania w sprawie
nadania stopnia naukowego doktora

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Wrocław, 04.09.23r.
miejscowość i data

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OŚWIADCZENIE

Oświadczam, że w pracy ***Marczak D.,*** *Lejcuś K., Lejcuś I., Misiewicz J. 2023. Sustainable Innovation: Turning Waste into Soil Additives. Materials. 16, 2900. DOI:10.3390/ma16072900,* mój udział polegał na zaproponowaniu i tworzeniu koncepcji oraz planu badań, sporządzeniu przeglądu literatury, przygotowaniu materiału badawczego, przygotowaniu biodegradowalnych geokompozytów sorbujących wodę, założeniu doświadczenia w warunkach rzeczywistych, doborze metodyki badań, określeniu wpływu geokompozytów na wegetację, analizie właściwości biodegradowalnych geokompozytów sorbujących wodę. Otrzymane wyniki opracowałam pod względem statystycznym i merytorycznym, przygotowując manuskrypt oraz wizualizację wyników, a następnie uczestniczyłam w redagowaniu tekstu w procesie recenzji i opracowaniu ostatecznej wersji publikacji.

Byłam wykonawcą w projekcie pt. Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin (nr POIR.04.01.04-00-0061/16; Narodowe Centrum Badań i Rozwoju), obejmującym badania zaprezentowane w niniejszej pracy.

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Potwierdzam treść oświadczenia.

04.09.23
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OŚWIADCZENIE

Oświadczam, że w pracy ***Marczak D.,*** *Lejcuś K., Lejcuś I., Misiewicz J. 2023. Sustainable Innovation: Turning Waste into Soil Additives. Materials. 16, 2900. DOI:10.3390/ma16072900,* mój udział polegał na współtworzeniu koncepcji badawczej i planu publikacji. Współredagowałem manuskrypt pod względem merytorycznym oraz pełniłem rolę autora korespondencyjnego w procesie publikacji.

Byłem kierownikiem projektu pt. Hydrobox2.0 – innowacyjna technologia wspomagająca oszczędzanie wody i wegetację roślin (nr POIR.04.01.04-00-0061/16; Narodowe Centrum Badań i Rozwoju), obejmującym badania zaprezentowane w niniejszej pracy.

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Oświadczam, że w pracy *Marczak D., Lejcuś K., Lejcuś I., Misiewicz J. 2023. Sustainable Innovation: Turning Waste into Soil Additives. Materials. 16, 2900. DOI:10.3390/ma16072900,* mój udział polegał na przygotowaniu, analizie i wizualizacji danych meteorologicznych.

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OŚWIADCZENIE

Oświadczam, że w pracy *Marczak D., Lejcuś K., Lejcuś I., Misiewicz J. 2023. Sustainable Innovation: Turning Waste into Soil Additives. Materials. 16, 2900. DOI:10.3390/ma16072900,* mój udział polegał na uczestnictwie w przygotowaniu doświadczenia terenowego i wizualizacji wyników badań. Uczestniczyłam w redagowaniu tekstu w procesie recenzji.

04.09.2023 Misiewicz
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