

## Revitalization of Virginia mallow culture (*Sida hemaphrodita* (L.) Rusby) for the isolation of cellulose fibers and the production of biofuels while meeting the requirements of a circular bioeconomy

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### Review

*This review paper analyzes the possibility of using the perennial crop of Virginia mallow (*Sida hemaphrodita* (L.) Rusby) to produce cellulose fibers. This culture was chosen, due to the previously established multiple applications, which, in addition to cultivation for food and medicinal purposes, include cleaning of the soil, increasing biological diversity, reducing soil erosion, and even the production of biofuels. The primary goal of this research was to determine the possibility of using the biomass (stems) of this plant for fiber production, that is, to determine the optimal conditions for fiber isolation. In cooperation with experts in the agricultural profession, the possibility of using the solid residue for energy purposes was examined. In the pretreatment process, the success of the combination of physical/chemical fiber treatment with the use of microwave energy was established, which not only shortens production time and energy consumption but also contributes to the ecological and economic aspects of fiber processing. The results of the conducted research confirmed the possibility of multiple applications of Virginia mallow biomass, first for fiber isolation, and then for the production of solid or liquid biofuels. The results indicate the possibility of revitalizing the mallow plant while meeting the goals of the circular bioeconomy and the European Green Deal, which is crucial for facing the challenges of climate change.*

**Ključne riječi:** *Sida Hemaphrodita* (L.) Rusby; solid biofuels; cellulose fibers; agricultural biomass; sustainability; bioenergy; European Green Deal; circular economy

### Pregled

#### Revitalizacija kulture Virdžinijskog sljeza (*Sida hermaphrodita* (L.) Rusby) za izolaciju celuloznih vlakana i proizvodnju biogoriva uz ispunjavanje zahtjeva kružnog biogospodarstva

*Ovaj pregledni rad analizira mogućnost primjene višegodišnje kulture Virdžinijskog sljeza (*Sida hermaphrodita* (L.) Rusby) za proizvodnju celuloznih vlakana. Ova kultura je odabrana, zbog prethodno utvrđene mnogostruke primjene koja osim uzgoja za prehrambene i medicinske svrhe uključuje čišćenje tla, povećanje biološke raznolikosti, smanjenje erozije tla, pa sve do proizvodnje biogoriva. Prvenstveni cilj ovog istraživanja bio je utvrditi mogućnost iskorištenja biomase (stabljike) ove biljke za proizvodnju vlakana, odnosno utvrditi optimalne uvjete za izolaciju vlakana. U suradnji sa stručnjacima poljoprivredne struke je ispitana mogućnost primjene krutog ostatka za energetske svrhe. U postupku predobrade je utvrđena uspješnost kombinacije fizikalno/kemijske obrade vlakana uz primjenu mikrovalne energije, što ne samo da skraćuje vrijeme proizvodnje i potrošnju energije, već također doprinosi ekološkim i ekonomskim aspektima obrade vlakana. Rezultati provedenih istraživanja su potvrdili mogućnost višestruke primjene biomase Virdžinijskog sljeza, najprije za izolaciju vlakana, a zatim i za proizvodnju krutih ili tekućih biogoriva. Rezultati ukazuju na mogućnost revitalizacije biljke sljeza uz ispunjavanje ciljeva kružnog biogospodarstva i Europskog Zelenog plana, ključnog za suočavanje s izazovima klimatskih promjena.*

**Ključne riječi:** *Sida hermaphrodita* (L.) Rusby; kruta biogoriva; celulozna vlakna; poljoprivredna biomasa; održivost, bioenergija; Europski zeleni plan; kružno gospodarstvo

## 1. Introduction

Every year we witness increasing climate changes, which are mostly caused by the warming of the atmosphere. Forests and oceans are being polluted and destroyed, while more animal and plant species are on the verge of extinction. One of the strategies that provide a solution for minimizing the negative consequences is the European Green Deal (EGD), which aims to transform the EU into a just and prosperous society with a modern, resource-efficient, and competitive economy by 2050 [1]. The main goal of this strategy is the transition to clean energy [2], circular bioeconomy, and complete mobilization of industry. It's necessary to reduce the amount of waste obtained from industries or try to use it completely.

In recent years, the focus of humanity has been increasingly focused on sustainable development. In 1987, the UN's Brundtland Commission, formerly known as the World Commission of Environment and Development, defined 17 priority goals aimed at meeting today's needs without endangering the needs of future generations. The goals of sustainable development are based on economic efficiency, social progress, and environmental responsibility. Growing awareness of the impact of economic growth on non-renewable energy sources and the environment has prompted a re-evaluation of the linear "take – use – discard" model. The circular economy, as opposed to the linear model, is becoming a key strategy of the EU and includes practices such as reuse, repair, recycling, eco-design, and responsible consumption. The first official document outlining the shift from an unsustainable economy towards the concept of circular economy was published in 2012 under the title "Towards Circular Economy", where its potential for creating financial savings was highlighted [3]. The use of resources in the circular economy is based on reducing their use and optimizing the use of by-products and waste with the intention of reducing the use of resources and the impact of production and consumption on environmental pollution. In principle, the main difference between a linear and circular economy lies in the adherence to the principles of sustainable development. A circular economy can be considered a sustainable economic system in which economic growth is separated from the use of resources, by reducing and recirculating natural resources [4]. Fig.1 shows the circular economy, which is based on the use of produced materials as long as possible, and waste is created only if there is no possibility of recycling.

In 2020, the EC presented a new circular economy action plan (CEAP) – for a cleaner and more competitive Europe, which strongly supports the goals of the EGD [6].

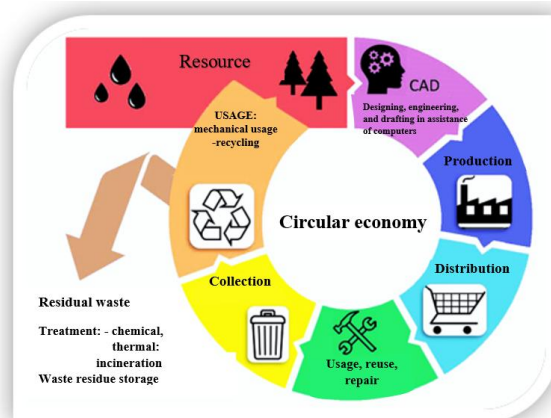


Fig.1 Basic principles of circular bioeconomy [5]

Achieving a circular economy requires changes in the entire value chain, from efficient resources management, product design, and new business and market models, to new ways of converting waste into resources and changing consumer behavior models. This includes the complete transformation of the existing economic model through innovation. A great effort should be invested in separating waste along the entire value chain, including every household [7]. One of the steps towards achieving a circular economy is the consumption of lignocellulosic biomass as an alternative to fossil fuels. Lignocellulosic biomass includes biomass after primary production, such as agricultural, forestry, and industrial waste, and represents the most widespread form of cheap, renewable, and high-energy biomass. It is used for the production of solid biofuels, i.e. wood chips, pellets, and briquettes, liquid biofuels, i.e. ethanol and diesel, and gaseous biofuels, i.e. biogas. Billions of tons of lignocellulosic biomass are produced every year due to growing industrialization and demand for food. Most lignocellulosic waste today is incinerated or discarded, polluting important water resources and posing an important environmental problem [8]. Agricultural biomass includes livestock, arable, horticultural, and further processing production. Currently, the greatest potential is shown by agricultural biomass from cereal crop production, industrial, and energy crops. The largest part of agricultural lignocellulosic waste refers to crop residues (different parts of the plant such as leaves, stems, husks, and roots, as well as biomass generated during the processing of the primary product, e.g. grains in cereals, in industrial plants or on farms) [9]. In the Waste Management Strategy of the Republic of Croatia (2005), it is pointed out that part of the agricultural residue generated in farming and the food industry is used for bedding and similar purposes, while a negligible part is used for energy production, and some part is left in the fields. Also, according to the estimation of the mentioned Strategy, 2 million tons of wheat residues,

2 million tons of corn, and 1 million tons of various fruits, vegetables, oilseeds, etc., are generated annually in farming, whereby 1.5 million tons of agricultural waste are generated annually [10]. For this reason, it is necessary to reduce the amount of agricultural waste that accumulates in the fields, to avoid burning lignocellulosic biomass in the fields, which is prohibited according to EU legislation, and it is necessary to repurpose such waste into raw material that will go back into the production process. Table 1 shows the most important sources of cellulose and lignin, among which is the Virginia mallow plant. Timely use of lignocellulosic biomass, can ensure a constant supply of raw materials and thereby achieve independence in the use of fossil fuels.

**Tab.1** Some of the valuable sources of lignocellulosic biomass [8]

Type of biomass	Source of lignocellulosic biomass
Agricultural waste	Crop residues from grains and oilseeds (corn, oats, rice, wheat, rapeseed, sunflower, etc.), biomass from energy crops ( <i>Virginia mallow</i> , <i>Miscanthus</i> , and <i>Arundo</i> ).
Forestry waste	Waste from oak, spruce, ash, beech, willow poplar, etc.
Industrial waste	Residues from fruit and vegetable processing (pits and husks), waste from wood processing, and the production of wood panels and furniture

The transition towards the circular economy is a challenging but essential process to address the climate change challenges we face today. A key component of the success of this transition lies in effective communication between different branches of the industry. Although the current transition phases may conflict with the established characteristics of long-lived linear economy models, with proper citizen education, promotion of initiatives, technological growth and research, a society that is fair, prosperous can be achieved, and abundant with a modern, resource-efficient, and competitive economy [4].

Agriculture represents one of the key economic branches of the European Union. Its sustainable management, including the use of agricultural biomass, i.e. energy crops, is key to fulfilling strategic goals. One such crop with enormous potential and a wide range of applications is the perennial energy plant *Sida hermaphrodita* (L.) Rusby from the *Malvaceae* family (mallows) [2]. *Sida hermaphrodita* (eng. *Virginia mallow*), reduces soil erosion, helps with its cleaning, increases biological diversity, is used for medicinal purposes, and as a raw material for biofuel production. The goal of this research was to determine its potential for use as a reinforcement for biodegradable polymeric matrix, i.e. for biocomposites.

## 2. Virginia mallow

Virginia mallow (lat. *Sida hermaphrodita* (L.) Rusby) is a perennial energy crop indigenous to Canada and the northeastern part of North America.

Morphologically, it can reach a height of 1–3 m. It has long and pointed leaves that grow alternately on the stem and usually consist of 3–7 irregularly serrated lobes with the middle one being the longest. Its stems are hairy in youth but become smooth over time. The flowers are white with 5 petals about 8 mm long, and bloom from August to October (Fig.2). This crop provides a significant source of lignocellulosic biomass, supporting a variety of industrial sectors, including paper and energy production. Its intensive cultivation emphasizes a significant potential in sustainable development and economy [11].



**Fig.2** The depiction of the upper part of the flowering stem of Virginia mallow [11]

Flowering begins in August and lasts until the first hard frost in October. The seeds are dispersed during winter and germinate in early spring. One adult plant can produce several thousand seeds, most of which are viable [11]. Saplings emerge from the soil at the end of April and beginning of May from the rhizomes of the plant. The lifespan of a cultivated plant is 15 to 20 years, with an expected 20–30 shoots in the fourth and subsequent years of cultivation. The first year of harvest has low biomass yields, while the highest yields were obtained in the 3rd and 4th years of cultivation [12]. Yield depends on soil and weather conditions, applied fertilizer, and weed control [13]. Virginia mallow thrives in open, moist, sunny to partially shaded coastal habitats. It grows on sandy soil with a low content of organic matter and a neutral to slightly acidic pH [11]. This plant species can thrive even on soils of lower productive quality, known as marginal lands, which is useful for the recultivation of degraded and polluted soils, and to avoid the exploitation of lands suitable for food production [12].

Despite claims of having no natural enemies, around 30% of the plants on the plantation can be infected with red spider mites and aphids. However, their harmfulness is low, so applying environmentally unfavorable protection measures is not recommended. Potential threats are also semi-bugs such as brown stink bugs (lat. *Coreus marginatus* L.) and various bugs such as the genus *Lygus*. as well as butterfly caterpillars [12].

### 2.1. The chemical composition of plant Virginia mallow

The potential of lignocellulosic biomass for biofuels is determined by its chemical composition. Agricultural waste (Tab.1), usually has a high cellulose and hemicellulose content and a low lignin content (<20%). The proportions of the mentioned components may vary depending on plant cultivation conditions, geographical location, age of the plant, and the method used to determine the chemical composition. In Table 2, various proportions of cellulose, hemicellulose, and lignin are shown, although the method of determining the lignocellulosic composition is the same for all the authors presented (modified standardized method ISO 5351-1:2002) [14]. Considering the chemical composition, agricultural waste is suitable for biofuel production, since biomass with a lower lignin content requires less energy-intensive processes for conversion into biofuel. Unlike agriculture biomass, forest biomass, with high lignin content, represents a technical and economic challenge [8]. The chemical composition of the Virginia mallow plant (Tab.2) includes a certain content of cellulose, hemicellulose, and lignin. The proportion of lignocellulosic composition in Virginia mallow depends on climatic conditions and the time of harvest (October, February, or March) [15]. The second and third harvest periods contribute to higher levels of cellulose and lignin in the plant, while the content of hemicellulose can increase or decrease. In the third harvest period, the biomass moisture content is typically less than 20%, facilitating further processing and storage.

Cellulose, as the main structural component, influences the strength of bast fiber. The percentage of cellulose in the natural fiber affects the application, properties, and production costs.

**Tab.2** Chemical composition of Virginia mallow plant according to selected researchers [2,14,15]

Chemical composition (%)	Source		
	[14]	[15]	[2]
Cellulose	42.65	39.03	39.93
Hemicellulose	29.17	30.08	26.84
Lignin	23.00	19.88	28.08

Hemicellulose, as a supporting matrix of cellulose microfibrils, significantly impacts fiber properties, while a higher hemicellulose content can increase moisture absorption. Lignin, a complex aromatic polymer, poses a challenge in extraction from biomass with high costs due to its hydrophobicity and insolubility in most solvents [16].

### 2.2. Potential Applications of Virginia mallow Plant

The sustainable supply of plant biomass represents a key challenge for meeting the needs of a growing economy, especially considering the increased share of energy from biomass. Cultivation of the Virginia mallow plant is becoming more and more important in order to strengthen renewable sources of resources and at the same time accumulate heavy metals from the soil in its biomass [17].

This perennial energy crop shows potential for cultivation on less fertile soils, thus avoiding competition with plants intended for the food industry. The cultivation of Virginia mallow in agriculture dates back to the middle of the last century when it was recognized as a fodder plant, a source of nectar for beekeeping, and a source of bast fiber for the textile industry. This rich history points to the various uses of the Virginia mallow plant, from agriculture to energy production, thus confirming its comprehensive contribution to various sectors [18-21].

Virginia mallow biomass is used in the production of pellets and briquettes [22], and their low heating value (LHV) is 19.9 MJ/kg [23]. However, it is also used for the production of low-density (LD) fiberboards. According to research [24], it can be used as a material for fiberboards, but the application of polymeric diphenylmethane diisocyanate (PMDI) resin as a binding agent was not successful as the properties of the composite deteriorated with the increasing mass fraction of Virginia mallow. It was found that the extract of Virginia mallow seeds showed strong antifungal activity, especially against the clinical strain of *Candida albicans*, with directed activity against other tested strains [25]. It is important to point out that this extract does not cause cytotoxic effects on fibroblasts, which opens the way for further research and development in biomedicine and is perceived as a promising candidate for the development of an antifungal drug against skin or systemic candidiasis.

Perennial crops can become an additional source of raw material for the paper industry due to their low nutrient requirements and high yields. According to research [26], the stem of Virginia mallow could potentially serve as an alternative fiber source for the paper industry in the future.

The main steps in pulp production are grinding, sieving, soda pulping, and beating. The stalks are ground by a hammer mill, cutting mill, or edge mill. The goal of grinding the stalks is to obtain particles of size 1–6 mm, so that the fibers are not too long for paper production and to increase the specific surface of the raw material and thereby improve the properties of the pulp [26]. The representation of the raw material of the stem of the Virginia mallow before and after grinding is visible in Fig.3. For the production of the pulp, a 10% NaOH solution was used, while the solid/liquid ratio was 1:20. The reaction temperature of  $98 \pm 2$  °C was maintained for 3 hours, after which the resulting pulp was sieved and washed with deionized water to pH 7 (Fig.4).



**Fig.3** The depiction of Virginia mallow stem before and after grinding by the hammer mill [26]

According to the obtained results [26], the average length of the cellulose fibers from the stem of Virginia mallow obtained for paper production is 1.3 mm. The conducted research revealed that cellulose fibers found in the pulp obtained from the mentioned plant show a satisfactory ratio of length to thickness and have good properties for the paper industry. Unbleached fibers are yellowish, demonstrate potential for high strength, and possible application in cardboard packaging, where good cellulose fiber bundle strength is required, without the need for bleaching. Through the implementation of the Design of Advanced Composites from Sustainable Energy Sources (BIOCOMPOSITES) project, led by the University of Zagreb Faculty of Textile Technology, in partnership with the University of Zagreb Faculty of Agriculture, two indigenous crops, including the

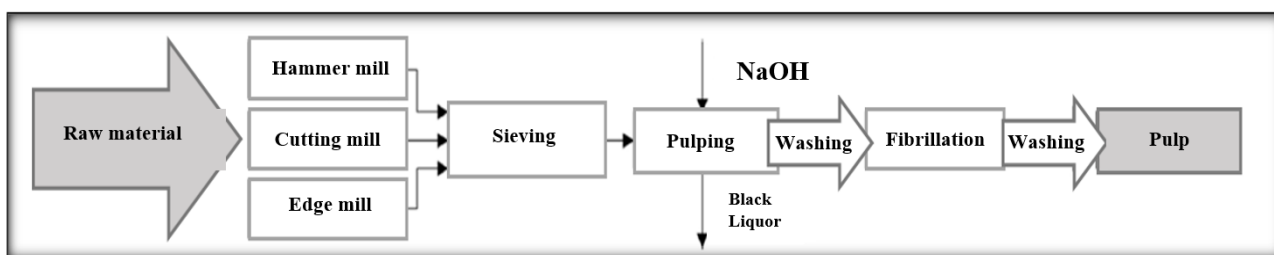
Virginia mallow, and prototypes of advanced biocomposite with long and short fibers were researched. The produced biocomposites are characterized by lower mass, improved strength, increased fire resistance, and additional antimicrobial properties. The developed materials can find applications in the automotive or construction industry. The BIOCOMPOSITES project has a positive impact on the textile and agricultural sectors, contributing to the Croatian bioeconomy, and confirming the assumption that agrowaste can have dual usage: in the production of biocomposites and biofuels [27].

### 2.2.1. Isolation of fibers from Virginia mallow

Although lignocellulosic biomass obtained from energy crops is primarily used to obtain energy, it is possible to use a part of it in the textile industry for obtaining cellulose raw material. Bast fibers, which are found in the longitudinal bundles of the stem, provide plants with strength and flexibility. These fibers are often as long-lasting as the stem from which they are extracted, making them an extremely valuable material [27,28].

Environmental pollution, long-term fiber isolation processes, and high levels of manual labor have contributed to the reduction of the bast fiber production. However, the modern development of new and more environmentally friendly technologies is reigniting the interest and demand for these fibers. They are considered one of the most sustainable and promising forms of natural fibers.

Retting or maceration refers to the process of extracting/isolating natural stem fibers, which implies the separation of fiber bundles from the cuticularized epidermis and woody core cells [28]. The method used to isolate the fibers directly affects the properties of the resulting fibers. Over the years, many methods of extracting fibers from plant stems have been developed, and we can divide them into manual, mechanical, chemical, biological, and physical methods or their combinations. A comparison between individual methods of extracting the bast fibers is shown in Tab.3. According to research [28], it was investigated three combinations of different fiber extraction methods: biological/mechanical, physical/mechanical, and physical/chemical. It was found that the physical/chemical method proved to be the best due to economic and environmental friendliness while re-



**SI.4** Production process of pulp from the raw material of perennial plant [26]

**Tab.3** Comparison of Different Methods for the Bast Fibers Extraction [30]

Extraction Method	Advantages	Disadvantages	Processing time
Water retting	fibers with uniform properties and high-quality	environmental pollution due to anaerobic bacterial fermentation, foul odor, and high costs, requiring intensive wastewater treatment	7 – 14 days
Dew retting	easy removal of pectin	the fibers are contaminated with soil, limited to specific climatic conditions, inconsistent quality	2 – 3 weeks
Enzymatic extraction	specific fiber properties are achieved by varying the time and type of enzyme (cleaner and faster process)	low fiber strength	12 – 24 hours
Chemical extraction	smooth and clean fiber surface in a short period	when the NaOH concentration exceeds 1%, it leads to reduced strength, high processing cost, and unfavorable color	60 – 75 minute
Mechanical extraction	large quantities of short fibers are removed in a short period	low fiber quality and high production costs	-

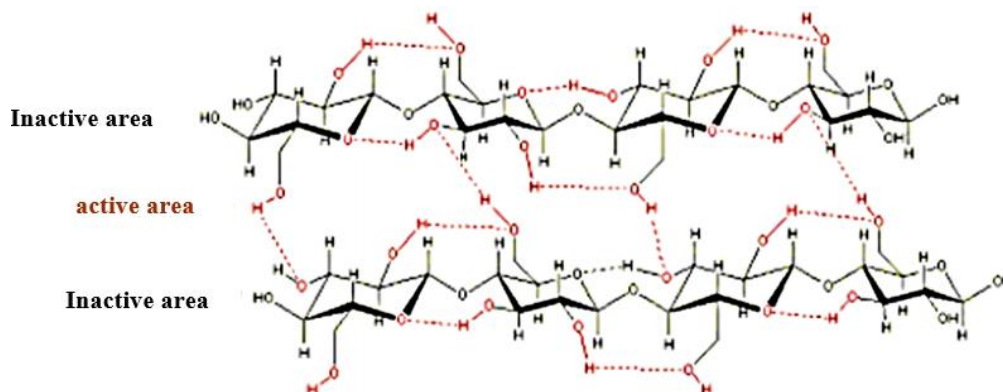
taining the good properties of the material. This type of method significantly speeds up the process and saves energy and is therefore more environmentally friendly, while conventional methods consume large amounts of water, chemicals, and energy and are environmentally less acceptable [29].

Chemical maceration assisted by microwave radiation (a chemical/physical fiber isolation process) has shown greater efficiency in removing non-cellulosic substances such as pectin [28], lignin, hemicellulose, and other accompanying substances from the plant compared to chemical maceration in an alkaline medium (NaOH) [29,31], and it has also resulted in a higher proportion of cellulose in the final product. With the MW treatment, electromagnetic energy penetrates the interior of the stem and interacts with the hydrogen bonds located in the cellulose, which increases the temperature and breaks the crystal bonds inside the cellulose (Fig.5).

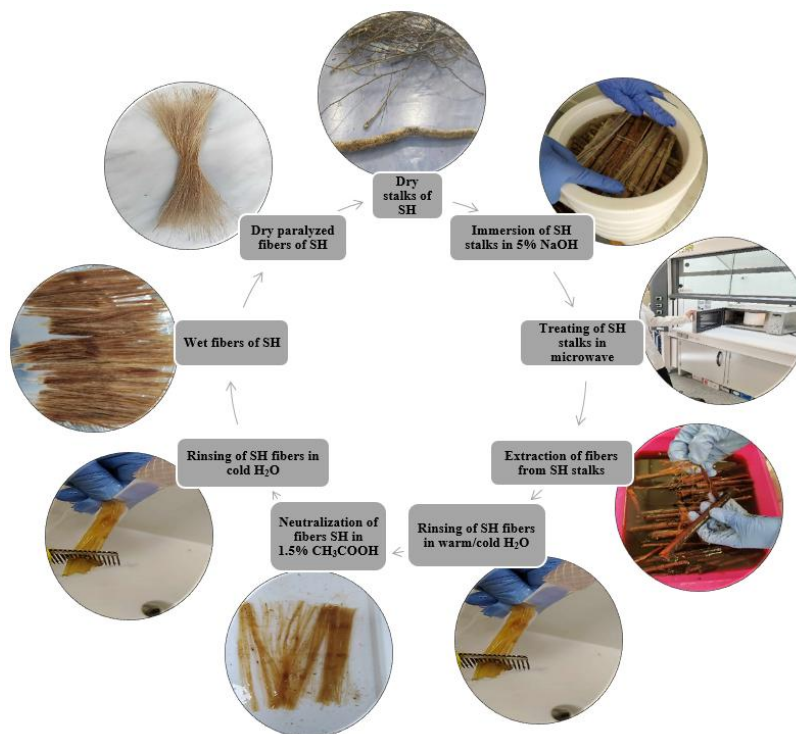
Also, due to the low polarity of the bonds, this type of treatment has an impact on the solubility of lignin in organic solvents such as NaOH. Chemical extraction in an alkaline medium under the influence of micro-

wave energy affects the removal of hydrophilic groups from hemicellulose and waxes, resulting in a more open surface of fibers with more pores, which allows us to directly influence the strength and bond between the fiber and polymer matrix in applications for biocomposite materials [32]. The process of obtaining fibers from the stem of the Virginia mallow using chemical extraction in an alkaline medium under the influence of microwave energy is shown schematically (Fig.6).

The properties of natural fibers, and thus the fiber content in the stem, can vary depending on biological diversity, growing conditions, climate, irrigation, harvesting method, the age of the plant and other factors. That can be supported by the results of the obtained values of the proportion of Virginia mallow fibers after chemical extraction in an alkaline medium for plants harvested in January 2020, which amounted to 10.71%, while those harvested in March 2021 had a fiber content of 11.97%. According to data [33], the proportion of fiber in the Spanish broom plant was 5%, which represents a smaller percentage compared to the values of other bast fibers.



**Fig.5** Active and inactive areas within the cellulose fiber under the influence of microwave energy [32]



**Fig.6** Schematic diagram of the process of chemical extraction of Virginia mallow stem under the influence of microwave energy

For example, in the case of research [34,35], the fiber yield in flax is 20-25 %. The production of flax per hectare is approximately 8 tons, and of Virginia mallow 20-25 tons, from which it follows that more fibers are obtained from the Virginia mallow per hectare than from flax [2,36,37].

### 3. Physical and mechanical properties of Virginia mallow fibers

The moisture content in textile materials, determined by air humidity, type of fiber, and sorption properties, is crucial for fiber performance and the implementation of physical/chemical method [37]. Natural fibers, including bast fibers, are hygroscopic and more comfortable to wear than synthetic. Moisture regain of various fibers, including those from Virginia mallow, is presented in Table 4.

**Tab.4** The moisture regain of Virginia mallow fibers compared to some of the most commonly used natural and synthetic fibers [28]

Fiber	Moisture regain (%)
Cotton	7-8
Flax	7
Virginia mallow	10-10.5
Wool	14-18
Viscose (CV)	12-14
Polyamide (PA)	4.1
Polypropylene (PP)	0
Glass (GF)	0

The conducted research showed that moisture regain of Virginia mallow fibers ranges from 10.0–10.5%. It can be concluded that Virginia mallow fibers exhibit good sorption properties similar to other cellulose fibers. Moisture absorption in the fiber is proportional to the content of amorphous regions within the fiber. The high hydrophilicity of bast fibers is caused by hydroxyl (-OH) groups within cellulose, hemicellulose, and lignin [32]. Fibers isolated from the stem by a combined physical/chemical method have a higher moisture content due to the successful removal of pectin, lignin, and waxes [28]. By removing lignin, which hinders moisture penetration into the cellulose cell wall, moisture absorption increases. The processing of Virginia mallow fibers due to chemical maceration in an alkaline medium affects the chemical composition, crystallinity, and structure, as well as the moisture absorbance of the fibers.

The characteristic densities of the selected bast fibers shown in Tab.5 are in the range between 1.19 g/cm<sup>3</sup> (willow fiber) and 1.57 g/cm<sup>3</sup> (Virginia mallow and kenaf).

**Tab.5** Density of Virginia mallow fiber and selected bast fibers characterized by selected researchers [39-42]

Fiber	Density (g/cm <sup>3</sup> )	References
Willow	1.19	[39]
Flax	1.38; 1.54; 1.45	[40]; [41]; [42]
Hemp	1.35; 1.43	[40]; [42]
Jute	1.23; 1.51; 1.34	[40]; [41]; [42]
Kenaf	1.57; 1.30	[41]; [42]
Virginia mallow	1.58	[27]

The average value of the density of Virginia mallow fibers, obtained using a gas pycnometer during the research [27], is 1.58 g/cm<sup>3</sup>, with a slight difference compared to the densities of other bast fibers listed in Table 5 [39-42].

The obtained density values include not only the cellulose content, which has a density of approx. 1.5 g/cm<sup>3</sup> but also other components such as lignin and hemicellulose. The density of pectin is probably similar to that of cellulose, which means that the presence of pectin does not cause significant variation in density. The morphology of the bast fiber, such as the presence of a central lumen, also affects density. For example, kapok fiber has a lower density (1.16 g/cm<sup>3</sup>) than jute fiber (1.45 – 1.5 g/cm<sup>3</sup>) due to its larger lumen. Other factors affecting variations in density include residual moisture, fiber extraction method, geometry, fiber porosity, and further processing and modification methods [43].

Natural fibers, due to their anisotropic structure, exhibit anisotropic properties. Stresses along the longitudinal fiber axis are significantly higher than stresses perpendicular to the fiber axis. The breaking force (F) represents the force at which the fiber breaks and the tenacity is expressed by the ratio of F to the fineness (linear density) of the fiber. Fineness, as a measure of cross-sectional area, is described by the ratio of fiber mass to length. The finer the fiber, the lower its linear density, and vice versa [37],

Biochemical diversity is key to the mechanical properties of bast fibers. The tensile strength and elastic modulus (Young's modulus) of fibers increase with increased cellulose content, while the presence of hemicellulose, due to its amorphous nature, leads to a decrease in fiber strength. Fiber strength is inversely proportional to breaking elongation, with higher-strength fibers having lower breaking elongation. The fineness of the bast fiber, related to the structural characteristics of the secondary cell wall (predominantly cellulose with a smaller proportion of lignin), depends on genetics, environment, shape, and length of the elementary fibers, their number in the technical fiber, and the method of fiber extraction [28,33].

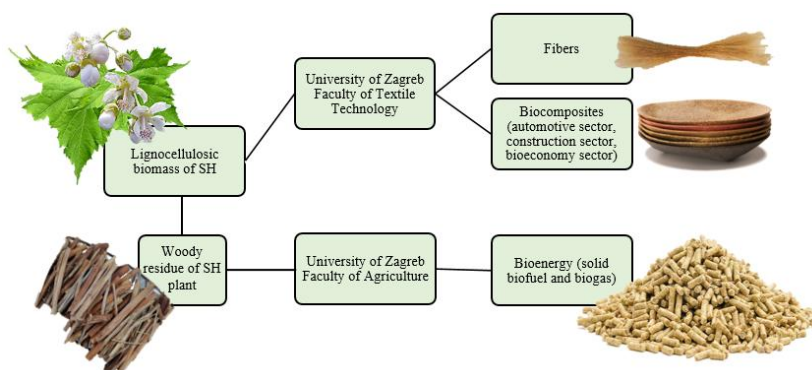
Tab.6 shows a comparison of the tensile strength and elongation at break of Virginia mallow fibers and other selected fibers. By comparing the results of tensile strength and elongation at break between the fibers of Virginia mallow and flax fiber as representative of bast fibers, it was concluded that Virginia mallow fiber shows satisfactory toughness and strength, and is compatible with other bast fibers, which makes it suitable for use in a wide range of products where a combination of lightness, strength and toughness is required.

Based on the above results, it can be concluded that the physical/chemical method of Virginia mallow fiber extraction can be successfully applied to isolate fibers with properties suitable for the textile industry and composites. Applying this method of fiber extraction leads to a significant shortening of production time and a reduction in energy consumption.

**Tab.6** Tensile strength and elongation at break of selected fibers [37]

Fiber	Tensile strength (cN/tex)	Elongation at break (%)
Cotton	19 – 42	5.6 – 7.1
Flax	26 – 77	3 – 4
Virginia mallow	73.48	5.81
Viscose (CV)	16 – 30	15 – 30
Wool	11 – 14	30 – 42
<i>p</i> -aramid (Kevlar)	140 – 250	1 – 4
Polypropylene (PP)	22 – 60	15 – 50
Glass (GF)	200 – 280	1.5 – 2

It is important to emphasize the fact that the woody residue, remaining after the isolation of the fibers from the Virginia mallow plant, which is unusable and represents waste in the textile industry, can be used as feedstock for biofuel production, thus contributing to the good practice of the circular economy. The complete utilization of Virginia mallow raw material, where the residue from biocomposite production will become raw material for biofuel production (Fig.7).



**Fig.7** Application of the circular model developed in the project Design of Advanced Composites from Sustainable Energy Sources (BIOCOMPOSITES) [27]

#### 4. Application of Virginia mallow for energy purposes

Agricultural lignocellulosic biomass, as a residue of primary agricultural production, represents a significant source of energy. Energy crops, such as the perennial species known as Virginia mallow, are key to biomass production. The goal of growing these crops is to achieve the maximum biomass yield per unit area, which can then be converted into energy. Energy crops enable different forms of biofuels, including solid fuels such as wood chips, pellets, and briquettes, liquid fuels such as biodiesel and bio-ethanol, and gaseous biofuels such as biogas [2].

Virginia mallow, as a perennial energy crop, has particular advantages, including the ability to grow in no-till systems and adaptation to marginal soils. Its ability to store nutrients, longevity of plantations, simple cultivation, and ability to adapt to different climate and soil conditions make it extremely promising for biomass production.

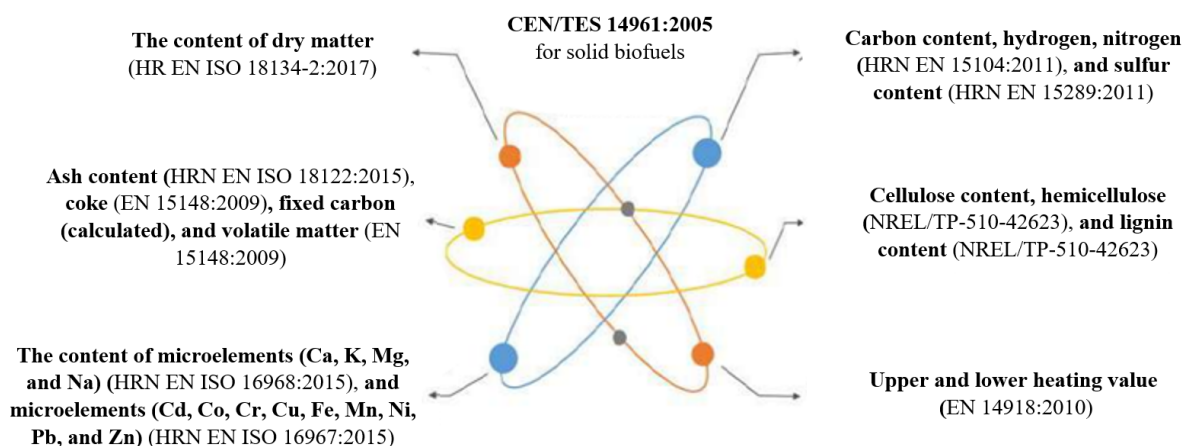
To convert a certain type of raw material such as *Miscanthus x giganteus*, *Sida hermaphrodita* L., *Arundo donax* L., or *Spartium junceum* L., into a potential source of energy in the form of biomass, it is necessary to thoroughly study their physical/chemical, structural and calorific characteristics. This research provides a deeper insight into energy efficiency, contributing to a better understanding of the potential for green energy production, as shown in Fig.8 [44]. Therefore, a study was conducted on energy production from Virginia mallow chips as a solid biofuel, analyzing combustible, and non-combustible matter, calorific value, and lignocellulosic composition [2]. Combustible properties refer to the characteristics of biomass that are relevant for its combustion or conversion into energy, while non-combustible properties refer to aspects of biomass that are not directly related to the combustion process or energy conversion.

Moisture, ash, fixed carbon, nitrogen, and coke content constitute non-combustible properties, while dry basis, carbon, hydrogen, oxygen, sulfur, and volatile matter represent combustible properties. The results of the research on the mentioned properties of Virginia mallow chips are presented in Table 7.

**Tab.7** Non-combustible and combustible matter content in the Virginia mallow residues after fiber extraction [2]

Non-combustible matter		Combustible matter	
Investigated parameters	Virginia mallow	Investigated parameters	Virginia mallow
Moisture (%)	8.03	Carbon (%)	48.97
Ash (%)	2.68	Hydrogen (%)	6.03
Fixed carbon (%)	5.45	Sulfur (%)	83.84
Coke (%)	8.13	Oxygen (%)	44.21
Nitrogen (%)	0.58	Volatile matter (%)	0.21

Carbon is a key element in all types of fuel and determines their quality; a higher carbon content makes the fuel of better quality. Along with carbon, hydrogen forms the basis composition of any fuel, and an increased proportion of hydrogen further expands fuel quality. By oxidation, carbon and hydrogen release energy and affect the calorific value. Oxygen, although it does not produce energy, supports the oxidation process. In agricultural biomass, the carbon content usually varies between 43% to 48%, hydrogen between 5% to 7% while the oxygen content on a dry basis is usually between 40% to 45%. The ash content in the fuel determines its quality, whereby a lower ash content is associated with a higher fuel quality. The content of coke and fixed carbon in biomass has a positive effect on energy characteristics, representing a significant amount of energy released through biomass combustion [2].



**Fig.8** Biomass analyses are conducted to determine its energy properties [44]

To determine the optimal type of fuel for a certain energy crop, it is necessary to analyze the strength, biodegradability, and flammability of the biomass, which is estimated using the lignocellulosic composition. If lignocellulosic biomass contains more lignin, then it is suitable for direct combustion, while a higher proportion of cellulose and hemicellulose makes the biomass suitable for the production of liquid fuels. The results of the lignocellulosic composition of Virginia mallow chips, which includes the proportion of cellulose, hemicellulose, and lignin, were obtained in the laboratory using the modified standard method ISO 535-1:2002 [14] and are shown in Table 8. These results indicate the possibility of using the investigated biomass for different types of biofuels, especially for solid biofuel production [2].

**Tab.8** Results of the lignocellulosic composition of Virginia mallow biomass [2]

Investigated parameters	Virginia mallow
Cellulose (%)	39.91
Hemicellulose (%)	26.84
Lignin (%)	28.08

The calorific value indicates the amount of thermal energy that can be obtained from biomass through conversion. The chemical composition and moisture content of the biomass have the greatest influence on the calorific value. The higher and lower heating values differ in their determination method [44]. According to the conducted research [2], the higher (HHV) and lower (LHV) heating value of Virginia mallow was 18.07 MJ/kg for the higher heating value and 16.75 MJ/kg for the lower heating value, indicating the high energy potential of researched culture. The higher heating value (H<sub>g</sub>, HHV) refers to the amount of heat produced by the complete combustion of a unit quantity of fuel. In this process, the flue gases are cooled to 25 °C, and the moisture from the flue gases is extracted as condensate. This represents the highest possible energy that can be obtained by burning a certain fuel. The lower heating value (H<sub>d</sub>, LHV) represents the amount of heat produced by the complete combustion of a unit quantity of fuel. In this process, the flue gases are cooled to 25 °C, and the moisture in the flue gases remains in the form of steam, not allowing the utilization of the heat of condensation. The lower heating value is subject to the influence of the moisture content and mass fraction of hydrogen in the fuel. It is lower than the higher heating value due to the heat used for the evaporation of water and sulfuric acid from the fuel or the water produced during the combustion process [44].

## 5. Conclusion

This review paper highlights the potential of the Virginia mallow plant (*Sida hermaphrodita* (L.) Rusby) and its potential revitalization for cellulose fibers extraction, while simultaneously adhering to the principle of circular bioeconomy through further utilization of the textile industry by-products for energy purposes. The achieved results indicate multiple applications of the plant, from the extraction of fibers and reinforcements in biocomposites to the utilization of residues for the production of solid biofuels.

The revitalization of Virginia mallow as a raw material for cellulosic fibers not only contributes to the textile industry in obtaining fibers and their application for clothing or biocomposites but also achieves the goals of a sustainable circular economy. The combination of the physical/chemical method of fiber extraction from the stem of the Virginia mallow under the influence of microwave energy has proven effective, shortening production time and reducing energy consumption. This technology also has the potential to improve the environmental and economic aspects of fiber extraction from plant stems.

The conducted research confirms the practicality of using the Virginia mallow plant for various industrial purposes and additionally promotes a sustainable approach through the full valorization of the plant, including the rest of the material after fiber extraction. This revitalization represents a step toward the realization of a circular bioeconomy, crucial for addressing the challenges of climate change and achieving the goals of the European Green Deal.

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