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Sustainable circular bioeconomy and agro-recycling: What do we know about banana fibre industry?

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Abstract

Background. The recycling of agricultural waste represents one of the practical directions for implementing the principles of circular bioeconomy. The use of biological residues or wastes for creation of environmentally friendly biodegradable materials is the way to achieving sustainable development. The cultivation of popular and nutritionally rich fruit of banana plants is associated with production of a large amount of biomass.

Purpose. This study is aimed to explore the potential of banana fibre under the concept of sustainable circular bioeconomy.

Materials and methods. To achieve the objective, we employ several methods such as an abstract-logical method, graphic method, comparative analysis method, data systematization and generalization. The empirical part of the study was derived from the statistical database from the Food and Agriculture Organization of the United Nations. The theoretical part of the study is based on the investigation the scientific literature from peer-review journals.

Results. The study showed that banana fibers are considered as an ecologically clean material capable of effectively replacing synthetic counterparts. An analysis of scientific papers revealed that presently the demand for utilization of banana by-products (pseudo-stems and banana leaves) for creation new products at the industrial level is growing around the world. We highlighted key botanical features of this plant and showed the banana plant potential for recycling. We found the largest banana and plantains producing countries. Thereafter, we summarized knowledge about the utilization of banana fibre in the textile and the paper industries as well as the biodegradable packaging materials.

Keywords: sustainability; circular economy; bioeconomy; biomass; circular bioeconomy; agricultural waste; banana by-product; banana fibre

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Устойчивая циркулярная биоэкономика и переработка сельскохозяйственной продукции: что мы знаем о производстве бананового волокна?

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Аннотация

Обоснование. Переработка сельскохозяйственных отходов является одним из практических направлений реализации принципов циркулярной биоэкономики. Использование биологических остатков или отходов для создания экологически чистых биоразлагаемых материалов – это способ достижения устойчивого развития. Выращивание популярных и богатых питательными веществами плодов растения банана (*Musa spp.)* сопровождается образованием значительного объема биомассы.

Цель – изучить потенциал бананового волокна в рамках концепции устойчивой круговой биоэкономики.

Материалы и методы. В ходе исследования был применен комплекс взаимодополняющих методов, включающий абстрактно-логический, графический, сравнительный анализ, систематизацию и обобщение данных. Эмпирическая основа исследования базируется на статистических данных Продовольственной и Сельскохозяйственной Организации Объединенных Наций. Теоретической основой исследования послужили научные труды из рецензируемых профильных журналов.

Результаты. Исследование показало, что банановые волокна считаются экологически чистым материалом, способным эффективно заменить синтетические аналоги. Анализ научных работ выявил, что в настоящее время в мире растет спрос на использование побочных продуктов производства бананов (псевдостебель и банановых листьев) для создания новых продуктов на промышленном уровне. Приведено ботаническое описание растения банан, что позволяет глубже понять потенциал данного растения для переработки. Определены и изучены крупнейшие страны производители бананов и плантайнов. Обобщены знания об использовании бананового волокна в текстильной и бумажной промышленности, а также в качестве биоразлагаемого упаковочного материала.

Ключевые слова: устойчивое развитие; экономика замкнутого цикла; биоэкономика; биомасса; циркулярная биоэкономика; сельскохозяйственные отходы; побочный продукт производства бананов; банановое волокно

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1. Introduction

The term circular bioeconomy is seen as a new economic paradigm which is directly connected to the principles of sustainability [1; 4; 8; 18; 23]. In recent years there is a growing interest to understand how bio-economic activities might be integrated into the total economy as a whole and contributed to achieving sustainable development. In scientific literature many papers are devoted to the exploration the boundaries between similar concepts: circular economy and bioeconomy. On the one side, bioeconomy deals with transforming renewable biological resources into various materials, chemicals and energy including food products, feedstocks, bioproducts and bioenergy that ensure competitiveness, economic development and low-carbon growth. Bioeconomy utilizes opportunities provided by bioscience and biotechnology to address economic, social and environmental issues [5; 18; 20]. On the other side, the concept of circular economy is associated with global industrialization and aims at reducing the impact of economic activity on the environment through reuse, recycling and restoration of materials during production processes and consumption. These two aforementioned concepts have come to be viewed as one unified concept known as circular bioeconomy. In the broad view, the promotion of the concept of circular bioeconomy is a consequence of global environmental challenges such as deterioration of the environment, climate change, rapid population growth, accelerated urbanization of large cities, accumulation of significant amounts of waste, energy resource deficit and depletion of fossil fuel reserves, which necessitate rethinking the existing economy based primarily on hydrocarbons [5; 24]. In this regard, there is an increasing need to transition from traditional linear economy to closed-loop circular bioeconomy.

Next, the concept of sustainable development is based on three concepts: social sustainability, economic sustainability and environmental sustainability. Sustainable circular bioeconomy constitutes three pillars, too. It should be mentioned that the circular economy intends to optimize the usage of resources and reduce generation of waste by three principles 3R, including reduce, reuse, recycle [5]. Circular economy and bioeconomy have overlapped. Several papers state [6; 8; 20] that bioeconomy is built upon the three directions: the ecological concept, the biomass-based bioeconomy and the biotechnology-based bioeconomy. Moreover, according to the review paper by Virgolino and Holden, the bioeconomy covers eight areas under the concept of sustainable development where one of them is related to sustainable consumption and the reduction of waste [27]. The concept of the circular bioeconomy has a root to the periodic and the efficient use of renewable non-fossil raw materials and products [25]. Figure 1 illustrates the interconnection between the above-described concepts, their principles and dimensions.

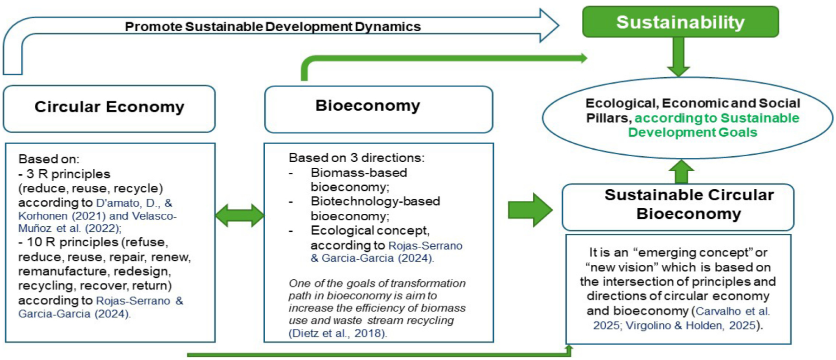

Fig. 1. Relation between circular economy, circular bioeconomy and sustainable circular bioeconomy

Source: compiled by the authors based on the following papers [2; 4-6; 23; 25; 27]

Agro-recycling is one of the applications of circular bioeconomy in the practice [25]. Usage of raw materials from agricultural waste and designing eco-friendly biodegradable products is a highly potential path to achieve sustainable development [4]. Banana fiber is seen as eco-friendly material which might partly substitute for synthetic fibre [3]. A number of studies about the utilization of banana by-products have significantly grown. Indeed, the production of banana plants has been characterized by a long history of crop cultivation by humans. The application of banana by-products under industrial level is an emerging topic under the sustainable circular bioeconomic vision.

This article addresses the questions: How useful is agricultural waste from the banana plant in the context of sustainability? What could we learn from the existing literature about the industrial potential of banana fibre? The aim of this article is to provide an overview of the applications of banana fiber and its connection with sustainable circular bioeconomy concept based on scientific publications.

2. Materials and Methods

The set of methods were applied under this work, including abstract-logical method, graphic method, comparative analysis method, data systematization and generalization. The study was built on the secondary data collection and analysis of scientific literature. The construction of the top banana producer ratings and the key regions of cultivated areas is based on the statistical database of FAOSTAT. The work was based on an analysis of scientific publications on the topic of using banana plant bioproducts within the circular bioeconomy concept. Literature search covered topics related to "biodegradable eco-friendly materials created from banana plants", "banana fiber" and "agro-biomass recycling". The literature for this study were searched via databases: Scopus, Google Scholar, SpringerLink.

3. Results

The banana plant (*Musa spp.*) is widely distributed and cultivated in the subtropical and tropical regions around the world [10]. It belongs to ancient forms of the plant community and go along with people since humans had begun their struggle with forests for creating crops adapted to their lifestyle [19]. The genetic diversity of Musa cultivars around the world is pretty high. Modern varieties of edible banana fruits have been genetically bred by combining two wild diploid species: *Musa acuminata Colla* (genome AA) и *Musa balbisiana Colla* (genome BB). At present, there are more than a thousand domesticated Musa cultivars in the world [10].

From the botanical view, the banana plant is one of the largest herbs which commonly grows up to 3 m in height [10]. In some case this giant plant can reach more than 5 meters [12; 17]. It should be mentioned that the banana plant is mainly cultivated for fruits. The fruit itself makes up about 12% of the entire plant. The exact proportion of biomass from the entire plant depends on the banana variety, so there may be some differences. Mostly, scientific literature states that 88% of the total plant mass is referred to the remaining parts of banana plant that is called banana by-products. Leaves, inflorescences, fruit stalks, pseudo-stem, and peels are banana by-products [26]. For instance, banana pseudo-stem is considered as a major part of the agricultural biomass and can likely contribute to the economy as renewable source [19]. Many papers argue that banana by-products are considered as the biomass or agricultural waste which have a great potential for recycling [11; 13; 16; 26].

Currently, bananas are grown in 135 countries around the world to obtain a nutritious fruit [15]. The term banana includes dessert bananas, plantains and cooking bananas. The differences between the three groups of the banana plant are related to the specific properties of the banana fruit and its usage [10; 15]. The statistical office of Food and Agricultural Organization (FAO) divides bananas into two groups. The first group are bananas (dessert bananas). The second group is plantains and cooking bananas [7]. The total annual production of banana fruits in the world amounts to 139.3 million tons (Table 1). India is the largest banana producing country with 26.3% of the total production in the world. The annual output of bananas in India is about 36.6 million tones. Top 15 countries of banana production are widely distributed by the world regions. The leading production countries along India in Asia are China, Indonesia, Philippines, Viet Nam. In the African continent there are Nigeria, Angola, Tanzania and Kenya. In Latin American countries the major banana producing countries belong to Ecuador, Brazil, Colombia, Guatemala, Costa Rica. All in all, the top 15 countries account for about 79.8 % of the world's banana production (Table 1). In 2023 the total production of plantains and cooking bananas fruits reaches 44.4 million tons. Uganda is the leading producer of plantains and cooking bananas with 25.0 % of the total production in the world. The annual output of plantains and cooking bananas in this country is about 11.1 million tones. Other main producers are DR Congo, Cameroon, Ghana, Philippines, Colombia. About 96% of the world's plantain and cooking banana production is formed by the top 15 countries (Table 1).

Table 1.

Top fifteen leading producers of bananas, plantains and cooking bananas by country in the world, in 2023

Bananas				Plantains and cooking bananas			
Rank	Country	Production (Mt)	Share of the total production (%)	Rank	Country	Production (Mt)	Share of the total production (%)
1	India	36.6	26.3	1	Uganda	11.1	25.0
2	China	11.7	8.4	2	DR Congo	4.9	11.0
3	Indonesia	9.3	6.7	3	Cameroon	4.6	10.4

4	Nigeria	7.3	5.2	4	Ghana	4.4	10.0
5	Ecuador	7.2	5.2	5	Philippines	3.1	7.1
6	Brazil	6.8	4.9	6	Colombia	2.6	5.8
7	Philippines	5.9	4.2	7	Côte d'Ivoire	2.1	4.8
8	Angola	4.9	3.5	8	Myanmar	1.4	3.2
9	Guatemala	4.4	3.2	9	Dominican Republic	1.3	3.0
10	Tanzania	3.7	2.6	10	Rwanda	1.0	2.4
11	Kenya	2.9	2.1	11	Ecuador	0.8	1.9
12	Mexico	2.6	1.9	12	Sri Lanka	0.8	1.8
13	Viet Nam	2.6	1.9	13	Guinea	0.7	1.6
14	Colombia	2.6	1.8	14	Cuba	0.7	1.6
15	Costa Rica	2.5	1.8	15	Venezuela	0.7	1.5
	Other countries	28.2	20.2		Other countries	4.0	8.9
	World	139.3	100.0		World	44.4	100.0

Source: own calculation based on the FAO STAT 2025 (retrieved 14.09.2025) [7]

The total cultivated area of banana constitutes 5973.3 thousand ha. The three key plantation banana regions by area are Southern Asia (18.6% out of the world), Eastern Africa (17.2%) and South America (16.7%). Area of production plantains and cooking bananas amounts to 6959.3 thousand ha in the world. The top three plantain and cooking bananas plantation regions are in Africa (Table 2).

Table 2.

Cultivated areas of bananas, plantains and cooking bananas by regions in the world, in 2023

Bananas			Plantains and cooking bananas		
Region	Cultivated area (thousand ha)	Share from the total cultivated area (%)	Region	Cultivated area (thousand ha)	Share from the total cultivated area (%)
Eastern Africa	1026.9	17.2	Eastern Africa	2907.4	41.8
Middle Africa	502.5	8.4	Middle Africa	1738.7	25.0
Southern Africa	10.1	0.2	South Africa	0.0	0.0
Western Africa	692.7	11.6	Western Africa	1147.9	16.5
Central America	234.7	3.9	Central America	61.3	0.9
Caribbean	132.7	2.2	Caribbean	170.2	2.4

South America	998.9	16.7	South America	503.5	7.2
Southern Asia	1111.5	18.6	Southern Asia	58.1	0.8
South-eastern Asia	683.8	11.4	South-eastern Asia	370.8	5.3
Western Asia	32.3	0.5	Western Asia	0.0	0.0
Other regions	547.1	9.2	Other regions	1.4	0.0
Total cultivated area in the world	5973.3	100.0	Total cultivated area in the world	6959.3	100.0

Source: own calculation based on the FAO STAT 2025 (retrieved 14.09.2025) [7]

4. Discussion

The recycling agricultural waste from banana plants after harvesting has a long history in the tropical and subtropical countries where this crop is grown abundantly.

One hectare of banana plantation generates around 220 tons of biomass [3]. Geographical distribution of banana production and size of cultivated areas shows that farmers from many countries meet the problems of how to utilize the banana pseudo-stem and leaves as agricultural waste after harvesting. For example, the largest amount of bio-waste is accounted for by the banana pseudo-stem. The extraction fibre from pseudo-stem is expected to reduce environmental problems [13; 26].

The transformation of banana cultivation by-products into non-food industry requires good knowledge about the properties of the plant passed down from generation to generation, on one hand, and creative and innovative solutions, on the other hand. Banana fiber is produced from banana pseudo-stems and has several eco-friendly applications such as textile industry, pulp and paper industry, food industry, and natural fibre-based composites. We will briefly view the application of banana leaves as an eco-friendly packaging material. We will take a closer look at banana fibre served ecofriendly and economical materials for on textile and paper industry.

4.1 An eco-friendly packaging material from banana leaves

The leaves of *Musa spp.* are used fresh as plates or plates for food, and packaging for steaming food because of their fiber content. In dry form, they are cut into strips for weaving various products and covering roofs of houses and shelters. The species most utilized for these purposes include *Musa ornata* and *Musa textilis* [10].

Compared to conventional plastic, a significant advantage of biodegradable materials such as banana leaf-based tableware and wrapping is that they do not contribute to the waste crisis caused by plastics and are relatively inexpensive and widely available in the banana-growing countries. Key characteristics include moisture retention prevention in foods and preservation of nutritional value during transportation. For instance, banana-leaf based product storage packaging has become increasingly common in Asian supermarkets [22].

The use of banana leaves as a wrapper for cooking dishes is quite widespread in Southeast Asian countries (for example India, Thailand, Malaysia, Sri Lanka) and in the Great African Lakes region countries (such as Burundi, Tanzania, Uganda, DR Congo, Kenya).

In India, especially in its southern states, leaf size is considered when setting the table, which is a unique practice. The large size of the leaf allows serving such multi-component dishes as rice, curry, and sweets. Thick leaves, particularly those of *Musa paradisiaca*, are used as wrapping food material because they retain moisture in the dish [12]. The filling wrapped in banana leaves is protected from the scorching effect of flame while retaining the aroma of the leaves [12; 17]. Leaves from banana plant are employed either for decorations or eco-friendly wrapping material for steaming, frying or grilling food in everyday life.

Furthermore, using banana leaves instead of foil and plastic packaging to preserve and cook food in banana-growing countries has been a long-standing tradition passed down through generations. In Burundi and Uganda, banana leaves are used to prepare dishes like Uburobe or Ubuswage. In this case, the banana leaf acting as a packaging material allows cooked vegetables to be preserved for several weeks [11].

Thus, banana leaves are being used in the food and non-food industry as environmentally friendly materials. The application of banana leaveы as packaging materials is actively developing in many countries. If earlier it started at the household level, today the use of banana leaves as packaging materials has moved to the industrial level.

4.2 Application in the textile and paper industry from banana pseudo-stem

The transformation of banana cultivation by-products into non-food industry requires good knowledge about the properties of the plant passed down from generation to generation, on one hand, and creative and innovative solutions, on the other hand. Banana fiber is produced from banana pseudo-stems and has several eco-friendly applications such as textile industry, pulp and paper industry, food industry, and natural fibre based composites. Next, we will take a closer look at banana fibre served ecofriendly and economical materials for on textile and paper industry.

Scientific publications provide insight into the history of production papers and textiles from banana fibre. For example, in Japan banana fibers can be used for the manufacture of general-purpose paper, banknotes, check paper, grease-proof paper. Banana fiber was employed in paper manufacturing both separately and in combination with other types of pulp [3; 9]. In the Philippines the banana fibre obtained from Abaca (*Musa textilis Nee.*) is the key source for textile [14]. The production of fabric from banana fibre has a long history in India and Bangladesh, too [17]. There is growing interest to new technology in African and South American countries.

Table 3 presents a short summary of review articles devoted to banana pseudo-stem as a valuable resource for advancing circular bioeconomy and sustainability.

Table 3.

Review studies of scientific literature on recycling biomass of banana pseudo-stems

Authors (year)	Journal	Key findings
Balda et al. (2021)	*Clean Technologies and Environmental Policy*	This study performs the comparison between various industrial applications of banana fibre by publications. The fiber content and strength determine the suitability of banana fibers for the different applications. Due to their high cellulose content and low lignin levels, banana fibers are ideally suited for the paper industry. This industry has a significant adverse environmental impact. So the usage of eco-friendly materials like banana fibre is expected to reduce the negative pressure on the environment.
Provin et al. (2024)	*Journal of Cleaner Production*	A systematic integrative review of the scientific literature on banana farming waste shows importance of banana fiber in the textile industry. This fiber can be considered as an alternative to synthetic and natural fibers such as expensive cotton. A study of 71 scientific papers revealed that banana fibers are characterized by excellent textile properties and environmental safety.
Vinay et al. (2024)	*Journal of Packaging Technology and Research*	The utilization of banana pseudo-stem in industry level grows. The investigation of the properties of banana fibre shows that this fibre is rich by elements like cellulose, hemicellulose and lignin. This study presents the holistic description of extraction methods of fibre from banana pseudo-stem which is grouped by mechanical, biological and chemical. Overview of diversity packaging materials derived from BPS is discussed. For example, diversity of applications from banana pseudo-stems include fiber, cellulose film, film, bioplastic film, etc.

Source: compiled by the authors based on the following papers [3; 21; 26]

5. Conclusion

In this article we focused on the biomass produced after the banana fruit harvesting and analyzed the publications related to the use of banana plant parts in non-food industry. Special attention is paid to two directions: leaves and pseudo-stems.

Having investigated the statistical data and the published scientific papers on this topic, we can draw the following conclusions:

1. This paper highlighted that the issues of sustainable development and the production of environmentally friendly materials and products from renewable bio-resources are an open space for discussion between science and business.

2. The results shown in this study pointed out that the production of bananas is growing around world. In this case, the search for ways to post-harvesting utilization from banana cultivation is an urgent task. Banana by-products is considered as the natural abundant raw material for the different environmentally friendly applications in industry based on principles of the sustainable circular bioeconomy. The properties of banana by-products allow them to be used for recycling and creating new products.

3. Pseudo-stem of banana plants are renewable sources for production of natural fibre with high quality. So that there is a huge demand for banana fibre in the textile industry to produce soft, low eco-footprint, biodegradable and hypoallergenic fabrics. Moreover, pseudo-stems have great potential for paper production due to their high cellulose content and low hemicellulose and lignin content compared to other non-wood materials. Paper production based on non-wood raw materials is more economical than wood-based paper production.

4. The findings allows us to make a statement that the integration of the banana waste valorization to produce textiles, paper and plastics might be a sustainable strategy rooted in the concept of circular bioeconomy.

5. We can suggest that as the production of the banana plant as an agricultural crop increases, it will be necessary to find new technological and innovative solutions for the use of by-products.

6. Future research can go deeply to investigate product sets manufactured from banana fibre and estimate their potential competitiveness compared to counterpart.

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