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Review

Rice-Husk-Based Materials for Biotechnological and Medical Applications

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Abstract: This review contains the main research directions, which are directly aimed at converting materials based on rice husks particularly, for their role for medicine and biotechnology. Especially in developing countries, more than 95% of rice husks are produced. Although numerous studies have been conducted on the production of various materials from rice husks, the existing scientific information is still widely scattered in the literature. Therefore, this review article provides extensive information on the work of various researchers, including the Institute of Combustion Problems (Almaty, Kazakhstan), on the production of various materials from rice husks and their physico-chemical characteristics. The main applications of rice husk materials in medicine are discussed. The ways of prospective conversion of rice husks for biotechnological purposes are considered.

Keywords: rice husk; carbon materials; cellulose; SiO_2; medicine; biotechnology

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1. Introduction

Rice husks are a multi-tonnage waste product from rice cultivation. Rice husks are used quite effectively as livestock feed, growing seedlings, and producing fuel briquettes, and they are used to make pyrolysis biofuel. A new trend in recycling is the addition of rice husks to building materials to improve their strength characteristics. Nevertheless, despite this, rice husk has attracted the attention of scientists, demonstrating the promise of rice husk processing to produce new types of materials with improved properties for use in various industries, including biotechnology and medicine. This review presents some results of rice husk product application in biotechnology and medicine, including the developments of researchers from the Institute of Combustion Problems (Almaty, Kazakhstan).

In today's world, there is a trend in biopolymers and bioplastics, which has turned researchers' attention to biowaste [1]. Biowaste is a valuable resource for obtaining functional materials that have found applications in various sectors, including biotechnology and medicine.

Rice husk (RH) is considered an agricultural biowaste that contains significant amounts of silica, carbon structures, and other minor minerals that have promising industrial and scientific applications. The bulk density of rice husk is low and is in the range of 90–150 $kg{\cdot}m^{-3}$. The main components of rice husk are shown in Table 1.

The main components of RH are cellulose, lignin, and silica, although their content may vary considerably depending on the variety and the region of germination. The increased silica content makes RH attractive for the production of silicon chloride, silicon carbide, and silicon nitride. All of the above examples show the versatility and potential applications of rice husk and its products, while its natural origin offers it biocompatibility and medical perspectives.

Table 1. The main constituents of RH in %. Reprinted with permission from Ref. [2]. Copyright 2018, Elsevier.

Rice Husk Main Components	Percentage, %	Rice Husk Main Components	Percentage, %
Volatile Matter	60–65	Cellulose	50
Fixed Carbon	10–15	Lignin Group	30
Ash	17–23	Silica SiO_2	20

This article, therefore, highlights the main applications of rice husk as an indispensable and accessible material for biotechnology and medical applications. New opportunities for wound care with nanostructured sorbents, which are obtained by the carbonization of rice husks, are also discussed in detail.

2. RH-Based Materials for Biotechnological Applications

The utilization of rice husk is a pressing issue worldwide and full application of this by-product by biotechnological methods is economically feasible and promising in the biotechnology industry [3]. The following examples are all known available attempts to use rice husks in biotechnology.

At the Institute of Combustion Problems (Almaty, Kazakhstan), new types of functional materials based on plant waste are being actively developed. A detailed description of the processes for obtaining carbon materials from rice husks is presented in the work [4].

The potential of RH in the production of bioplastics is addressed in [5]. Relying on life cycle assessment (LCA), the authors investigated the environmental impact of bioplastics and the environmental costs of converting RH compared to conventional recycling. This study evaluated the production of three different biodegradable bioplastics from carboxymethyl cellulose, cellulose acetate and cellulose nitrate separated from rice husks. The results of the work carried out determined that, in general, RH has excellent potential for use as a bioplastic. However, carboxymethyl cellulose appears to be the most effective among the various bioplastics produced. According to the authors, sulfuric acid can be used as a substitute for nitric acid in the hydrolysis process.

Due to the increasing consumption of single-use products and the need to reduce plastic consumption, scientists have identified an alternative option for producing bio-based containers. A potential material with a number of features befitting a high-quality plastic or ceramic, such as rice husk, would play a major role in the making of bio-wares. In countries where rice by-products are abundant, the usage of RH-based containers is widespread. The development of biodegradable utensils has taken off on a vast scale in India [6] and Singapore [7]. The famous Bacardi brand, for example, has also launched recyclable glasses and glasses made from rice husks [8], while there are open markets selling all kinds of RH home products, including for children, with bio-safety ingredients [9].

Cespugli et al. [10] have considered rice husks as an affordable, renewable carrier for the immobilization of biocatalysts used in the food, cosmetics, and polymer industries. This study demonstrated the potential applicability of rice husk as an inexpensive renewable carrier for enzyme immobilization in applicable sectors where covalent protein fixation is essential to prevent protein contamination while providing recyclability. Based on their research, the authors found that, by dispersing the enzyme on the surface of an inexpensive carrier, maximum mass transfer is achieved (Figure 1). Ergonomic rice husk was also effectively used in aqueous solutions as a carrier for various enzymes that catalyze hydrolysis. The immobilized enzymes used showed optimum dispersibility and reusability. According to the authors, the results indicate that the immobilization of enzymes on large volumes of available renewable carriers reduces the environmental impact of fossil-based carriers, increasing the economic and environmental efficiency of the processes.

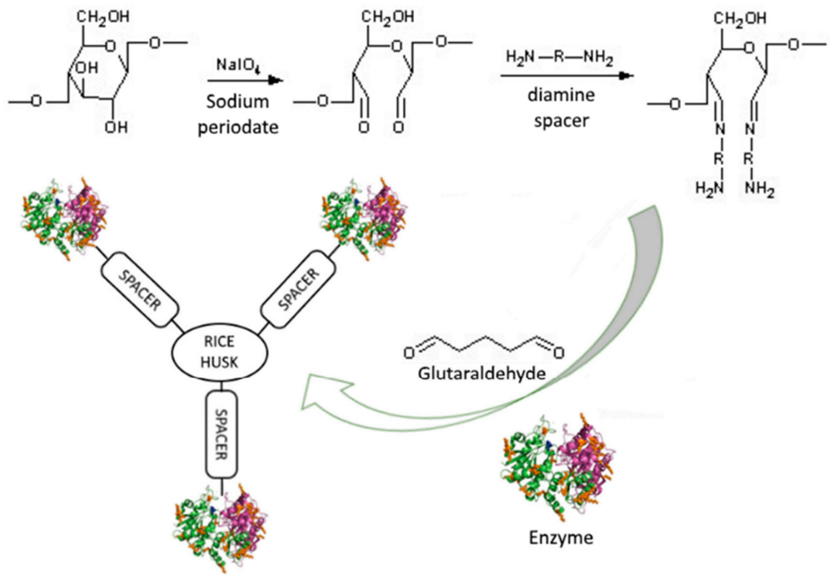
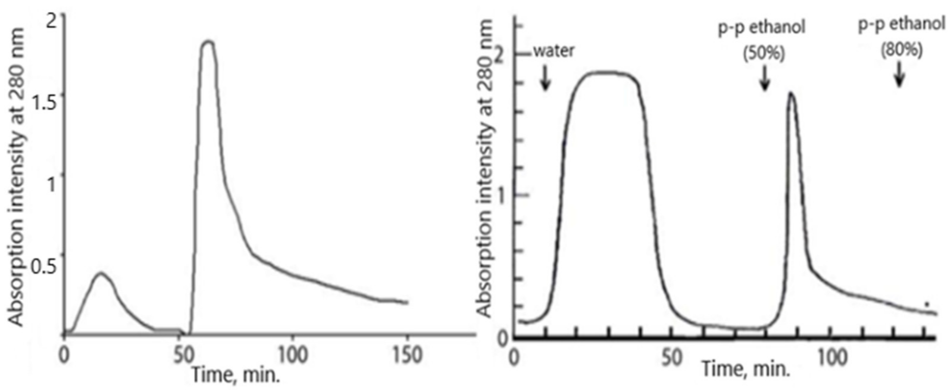


Figure 1. Schematic illustration of the oxidation and functionalization of the cellulosic fraction of RH for the covalent immobilization of Lipase B from Candida Antarctica. Reprinted with permission from Ref. [10]. Copyright 2018, MDPI.

The article [11] examined the potential application of rice husk as an environmentally friendly bio-resource for the production of butanediol. 2, 3-butanediol has a wide range of applications, ranging from petrochemicals to widely used food and pharmaceuticals in many industries. It is traditionally produced by various sugar-fermenting microorganisms, such as *Bacillus amyloliquefaciens*, *Bacillus subtilis*, *Enterobacter aerogenes*, *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Lactococcus lactis*, *Paenibacillus polymyxa* and *Serratia marcescens*. Given the fact that all the above microorganisms are classified as risk group 2, according to the World Health Organization, the microbial production of 2,3-butanediol from rice husks using *Clostridium* species was investigated in this study. Rice husks contain significant amounts of sugars, such as cellulose and hemicellulose, which can be converted into valuable products such as 2,3-butadieneone and 2,3-butanediol [11].

One of the important areas of RH processing is the production of sorbents due to the porous initial structure. These sorbents can be used not only for direct purification but also for the extraction of valuable components. In [12,13], studies on the extraction of fusicoccin on a sorbent from rice husk were presented (Figure 2).



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

Figure 2. Fusicoccin chromatographic separation curves on column with carbonized RH (**a**) and octylsepharose 4B-CL organic gel (**b**). Reprinted with permission from Ref. [14]. Copyright 2007, KazNU.

The next work was carried out by researchers of the Department of Animal Science, Brawijaya University, Malang, Indonesia to obtain high-quality feed from rice husks. Detailed data and the results of the work carried out in this area are presented in [15].

Since RH has a limiting factor as shown by its ash or silica content, according to the authors of the work, liquid waste from biogas production can be used to improve the quality of feed, i.e., RH. During the performance of the nutrient content, incubation time and temperature were important factors. The authors found that the addition of 15% liquid biogas waste ($mL \cdot g^{-1}$) with an incubation time of 21 days provides the best quality rice husks based on improved crude protein, crude fat, and gross energy content with the lowest crude fiber content. Extensive research has been carried out by scientists over the years to obtain biochar from RH. In many works by a number of scientists, it has been established that biochar isolated from RH has a very wide range of applications. Numerous scientific papers have been devoted to its characterization and the monitoring of its effects on soil content and productivity [16,17].

Additionally, many publications have been devoted to the positive prospects of using biochar in combination with other bio-objects. An example of this kind of work is the research work of Wei Wang et al. [18]. As noted by the researchers, the combined addition of eggshells and rice husk produced the highest quality compost in the shortest possible time. To obtain a stable and mature product, the two-step composting of green waste needed 30 days without additives, but only 20 days with the combined addition of 10% ESW and 25% RH. As noted by scientists in their work, the above combination has also shown itself to be beneficial as a stabilizer of clayey soils as well as a neutralizer of acidic soils [19].

Some research papers have also described the negative aspects of using biochar as fertilizer [20]. The addition of biochar has attracted more attention because of the impact on the soil's nematode community. The application of biochar directly alters the physico-chemical properties of the soil, such as pH, porosity, and aggregate components. This also changes the microbial community, which can alter the composition of soil nematodes through their interaction. As part of the rational use of biochar from RH, extensive experiments have been conducted to determine the optimum dosage of biochar application. The studies have determined that a low dose of biochar can be applied to stimulate omnivores and nematodes with highly functional guilds that are most sensitive and have difficulty recovering from problem soils.

Biochar, widely used in agronomy, also has positive aspects of use as an adsorbent or insulating powder. RH is regarded as a versatile and low-cost absorbent for oil and oil pollutants. For example, Chen-Yu Tsai et al. developed mesoporous bio-carbon derived from rice husk to effectively remove malachite greens from wastewater [21].

Rice husk and apricot kernel sorbents were obtained from the Institute for Combustion Problems and tested for the adsorption of various petroleum products [22]. The sorbent based on RH showed the best performance (Figure 3).

The modified adsorbent obtained by hydrothermal alkali activation showed a good green removal performance. This methodology was excellent for the production of modified biochar (RHMB). This method significantly increased the adsorption activity of the modified sorbent. The BET results showed that the pore volume of RH increased significantly by about 18.7 times and also led to the formation of richer OH groups on the adsorbent surface. It is worth noting that, during removal, the main adsorption contacts were H bonds and π–π interactions at pH 6. When tested in the river and sea water, it showed that the obtained adsorbent maintained an outstanding removal efficiency (>96%) and was not subject to ionic interference even at high salinity.

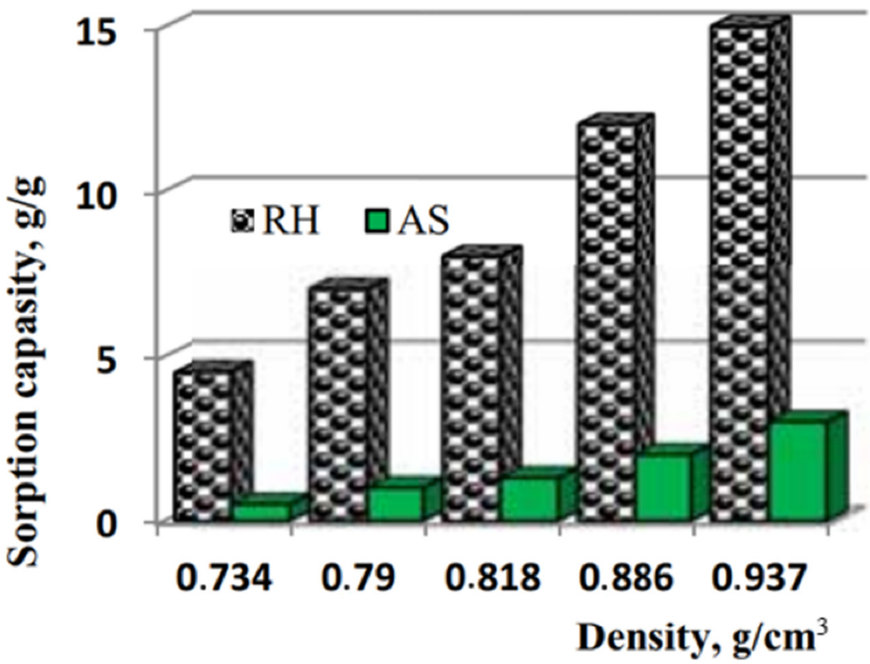


Figure 3. Sorption characteristics of carbonized rice husk and carbonized apricot stone as a function of petroleum product density. Reprinted with permission from Ref. [22]. Copyright 2014, Ministry of Education and Science of the Republic of Kazakhstan.

Rice husks are a significant source of cellulose-rich biomass, and in the future, there is great interest in converting them into a complete product. To date, the potential of RH in papermaking has been little explored, but publications in this area are considered promising. An example of such work is the study of Rashid S et al. [23], where cellulose from rice husks and nanocellulose, isolated by scientists, could be applied in the development of various heat-resistant materials and as a safe ingredient in various consumer products. According to the authors, such applications contribute to rational waste management and enhance the value of these major wastes in the rice industry.

Pedro Nascimento et al. proposed the use of rice husks to produce cellulose nanofibers using peracetic acid as a more environmentally friendly bleaching agent. Their article details the main characteristics of cellulose nanofibers derived from rice husk. One of the most important points of the study is the combination of nanofibers with a starch-glycerol film. The authors noted that the addition of nanofibers resulted in opacity, vapor permeability, and improved mechanical properties of the starch films (Figure 4). These results indicate that this renewable source of agro-industrial waste has promise as a reinforcing agent in polymer composites [24].

The application of RH as food packaging was addressed by Sánchez-Safonta et al. [24]. All the fibers investigated demonstrated their suitability for use in the development of fully compostable biocomposites. The promising results obtained suggest a promising starting point for the valorization (rice husks and almond shells) of waste materials in industrial food packaging applications [25].

Nashiruddin et al. produced mycelial biofoam based on the fungal mycelium Pleurotus ostreatus and lignocellulosic material as matrix and substrate as an alternative to oil polymer foam. Rice husk, sawdust, and sugarcane cake were selected as potential substrate materials. During mycelium-based bio-foam production, three growth factors were varied: incubation temperature, egg loading, and moisture content. Based on the results of the study, it can be said that rice husk was quite the ideal substrate for mycelial bio-foam production [26].

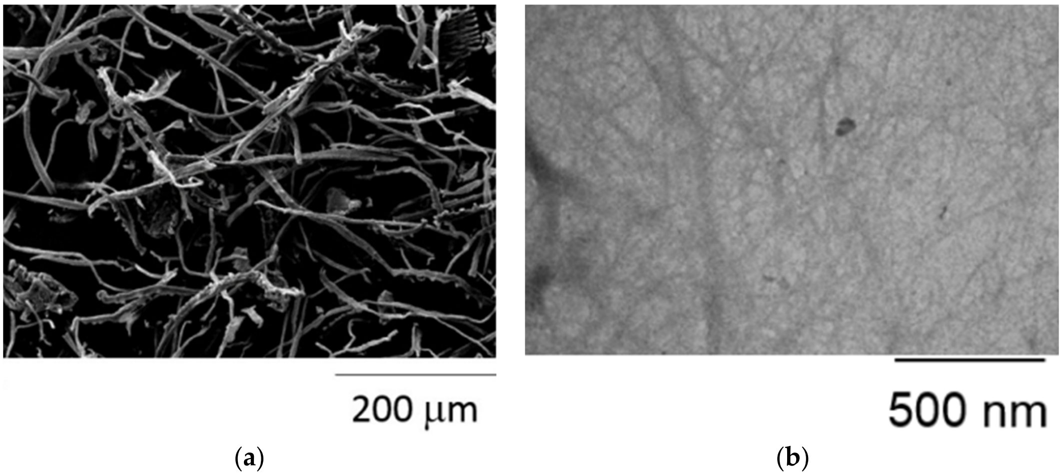


Figure 4. (**a**) Micrograph obtained using SEM of rice husk treated with NaOH followed by peracetic acid, and (**b**) micrographs obtained using TEM of the cellulose nanofibers from rice husk (extraction at 2 h). Reprinted with permission from Ref. [24]. Copyright 2016, Materials Research.

Many studies have been published in the scientific literature about the possibility of producing liquid and solid biofuels [27,28]. For example, in the works of Shubhra Tiwari et al., RH is presented as powerful lignocellulosic biomass for bioethanol production [29].

3. RH-Based Materials for Medical Applications

Around 600 million tons of rice husks are thrown up every year in the world [2]. Most of it is burned in ovens or disposed of in a land-intensive manner. Nevertheless, the interesting thing is that the husks do not disintegrate in the ground due to the presence of silicon dioxide in them. In addition, when the husks are burned, they release substances that can have a negative impact on nature and human health. The disposal of rice husks is an urgent problem worldwide, especially in countries where rice is the main cereal product (China, India, Egypt, and South Korea, countries in Africa, and partly Russia, Kazakhstan, and Uzbekistan). The processing of rice husks to produce materials for medical applications has been developed in several main directions: SiO_2, cellulose, protein extraction, and the production of carbon materials to produce sorbents.

SiO_2 is a competitive material that has found application not only in the energy sector but also in medicine. As rice husks are a bio-organic source of silica, their use in medicine is important. A particularly strong viral infection became topical after the COVID-19 pandemic. Scientists were looking for a way to modify various drugs to fight such types of viruses. Suman S. et.al. used ash from rice husk as a carrier to substitute an antiviral drug. The drug has a heterocyclic compound known as Imidazole [29].

The latter is a powerful heterocycle and an antiviral active ingredient among other drugs. The synthesis of the substituted Imidazole takes place in one step and the method is simple and accessible. Figure 5 shows the synthesis scheme with aldehyde—0.1 mmol (1–7), benzyl—0.1 mmol (8), ammonium acetate—0.2 mmol (9), and rice husk ash SO_3H—(0.50 g) by stirring at room temperature in a 50 mL round bottom flask.

Scientists found that ash from rice husk SO_3H has the best catalytic activity in terms of product yield, solvent, and reaction time compared to other biocatalysts. The work also tested successfully for herbicidal and antifungal activity of the obtained preparation at different concentrations, which showed slow growth when interacting with Imidazole.

Thus, the abundance of RH makes it readily available and inexpensive as a catalyst for obtaining an antiviral drug. Scientists have highlighted the catalyst's renewability, which in turn is a highly valuable resource in terms of green chemistry.

Silica is not only used as a biocatalyst but also as a drug carrier for delivery to cancer cells. In recent years, with the increasing number of cancers, such as breast, lung, intestinal, uterine, brain, and skin cancers, scientists are looking for different ways to treat them on a nanoscale level.

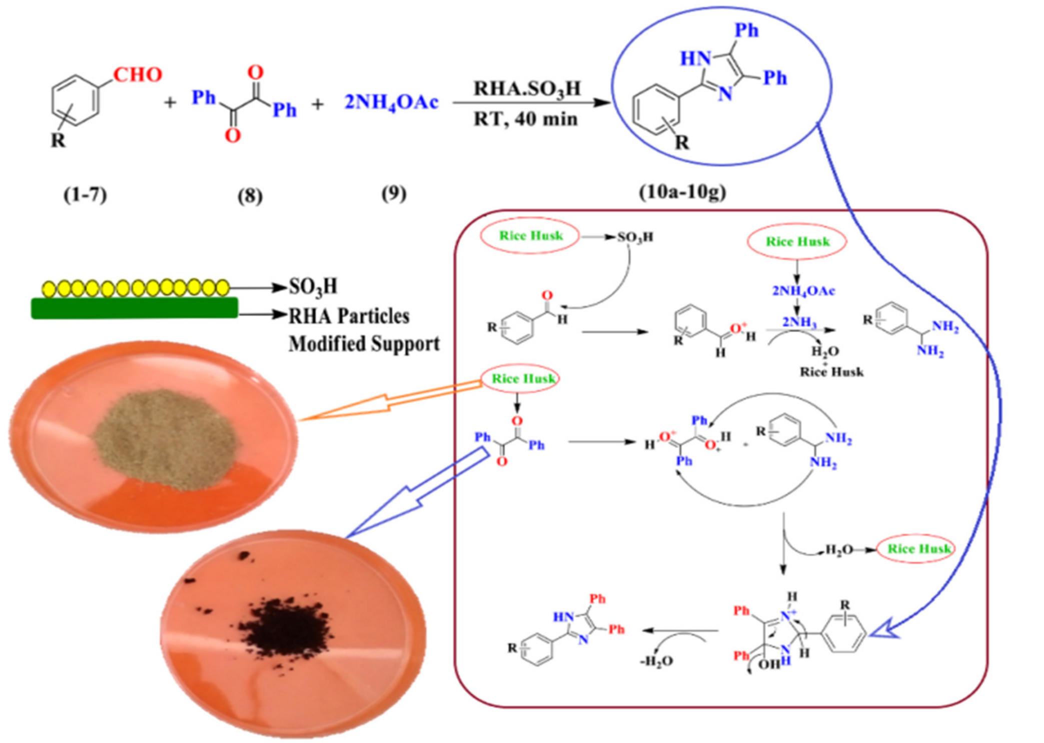


Figure 5. Scheme for the synthesis of Imidazole with RH ash. Reprinted with permission from Ref. [30]. Copyright 2022, Elsevier.

In [31], for example, the authors extracted silica from rice husks by a chemical-thermal process with further washing and treatment to deliver an anti-bullet drug to the cancer cell.

The authors show the possibility of obtaining biocompatible silica from rice husk, which is confirmed in [32]. The next step was to obtain lower-sized particles for high-quality drug delivery into the cancer cell. The authors obtained silica nanoparticles (SiNPs) using the Stober method [33] according to the scheme shown in Figure 6. The authors used Fluorouracil (5-FU) as an anti-cancer drug and functionalized with silicon dioxide using two different methods.

The authors have carried out test work on the effect of silica nanoparticles on the cancer cell, which as a carrier of silica nanoparticles shows itself to be very good. The work includes a complete before and after analysis of the drug substitution into the silica nanoparticle. The cell culture with the drug delivery mechanism is also shown.

The scientists emphasize the importance of the nanoscale of silica, because the structure of cancer cells is dense and nanoscale particles easily penetrate the cell and release the drugs. The paper also talks about the control of drug delivery controlled by a chemical osmotic system. The importance and efficacy of silica in the delivery of anti-cancer drugs is noted since they have excellent biocompatibility and low toxicity [31,34,35].

As silica from rice husks is a highly pure component, i.e., has no foreign impurities, it is also used to make biocompatible glass. In [36], the authors obtained bioactive glass based on ash from rice husks. As mentioned above, scientists have found another way of drug delivery using bioactive glass made from rice husk ash. Thus, in [37], the researchers extracted silicon dioxide from rice husks by acid–alkaline precipitation at 600 °C and prepared bioactive glass by further drug loading using the sol-gel method [38,39].

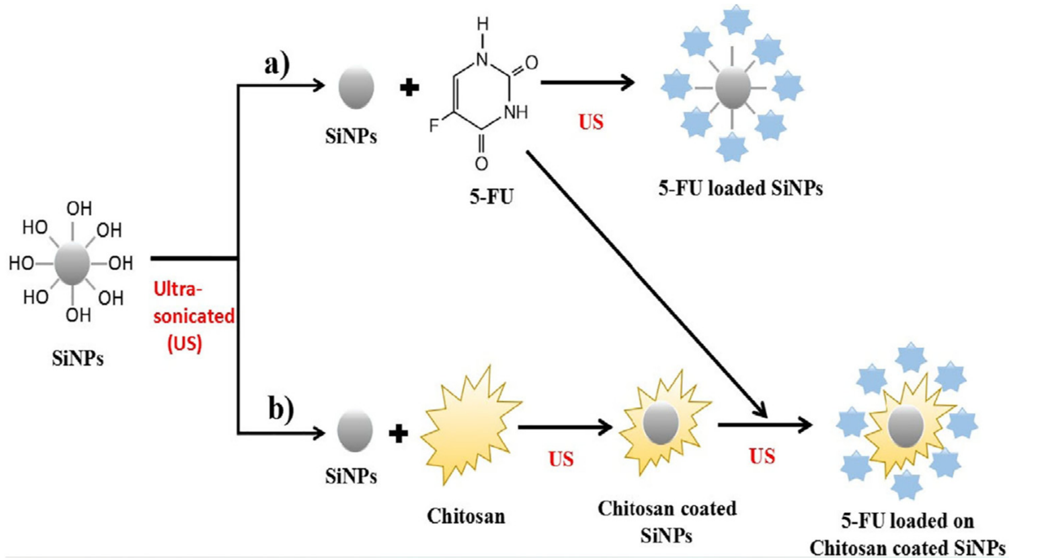
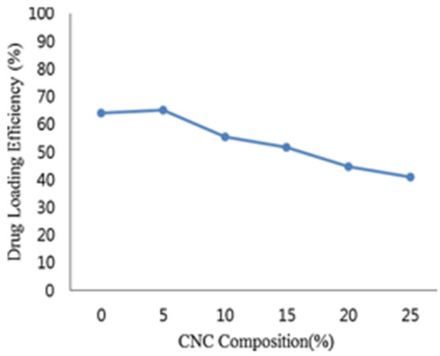


Figure 6. Schematic of the functionalization of 5-FU on SiNPs by (**a**) Direct conjugation (SiNPs conjugated with 5-FU) and (**b**) indirect conjugation (chitosan-coated SiNPs conjugated with 5-FU). Reprinted with permission from Ref. [31]. Copyright 2020, Elsevier.

The synthesized bioactive glass was found to have a similar micro-hardness to that of human bone. This means that these synthesized glass samples are effective bioactive materials.

Not only can silicon dioxide be used in drug delivery, but another constituent of rice husks, cellulose nanocrystals (CNC), can also be used. Scientists in China produced the first cellulose nanocrystals [40] in 2011. Even then the basic characteristics of CNC, such as large surface area, high mechanical strength, high aspect ratio, hydrophilicity, non-toxicity, low bulk density, biocompatibility, and biodegradability, were investigated, which can be used as reinforcement material in polymers.

Thus, ref. [41] used gelatin hydrogels reinforced CNC, which was obtained by chemical crosslinking for easy release of drugs from the gelatin framework. The authors found that the efficiency of drug loading and drug release properties of hydrogels were related to the degree of hydrogel swelling (Figure 7).



CNC composition (%)	Drug loading efficiency (%)
0	64.2
5	65.3
10	55.5
15	51.7
20	44.8
25	41.1

Figure 7. Drug-loading efficiency of cellulose nanocrystal–gelatin hydrogels and drug-loading efficiency data for gelatin hydrogels and CNC gelatin hydrogels reinforced with different amounts of CNC. Reprinted with permission from Ref. [41]. Copyright 2016, Elsevier.

The results showed that the highest drug-loading and drug release rate were achieved using a gelatin hydrogel reinforced with 5% CNC. However, gelatin hydrogels reinforced with 15% CNC showed the best balance of drug-loading and controlled drug release properties, making it a good candidate for further study in a drug delivery system.

The protein content of rice husk has to date received little attention, although scientists [42] have recently identified anti-cancer activity and potential clinical applications of rice bran extracts and fermentation products. Peptides are known to exhibit not only antioxidant, antihypertensive, antityrosinase and anti-inflammatory activity in human embryonic kidney cells, but also show no toxicity or irritant effect in a human reconstructed epidermis model, so the extraction of peptides from cereal products is a relevant direction to support human health.

In [43], scientists obtained protein extraction from rice husks. This work involves the extraction of rice husk with hot water, which has been optimized to produce a protein hydrolysate with the highest anticancer activity.

Carbon materials are widely used in medicine, especially in recent years, scientists have been trying to obtain carbon dots for various respiratory systems. For example, the authors of the work synthesized carbon dots for a mask that can be used for diabetic patients because diabetic patients emit a large amount of air with an acetone odor when exhaling. Conventional masks are powerless against the strong odor, so the idea is to obtain masks with carbon dots that can be obtained from rice husks. In the work, the carbon dots were synthesized by hydrothermal method and deposited in a cotton cloth (Figure 8).

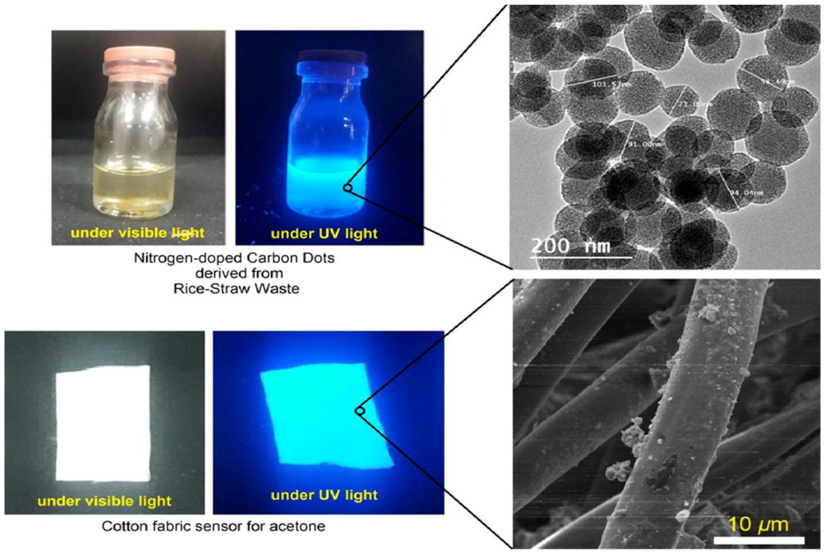


Figure 8. Visual diagrams of the replacement of carbon dots on the mask fabric and its UV light test. Reprinted with permission from Ref. [44]. Copyright 2022, Elsevier.

It has been found that rice husks can be converted into valuable nanoscale materials, which can then be used to develop a sensor assay for detecting acetone as well as for monitoring diabetes [44].

Depending on the processing conditions, RH carbon materials can have different morphology and structure, making them suitable for different applications. The studies [45] have demonstrated that the use of nanostructured carbon sorbents from RH can indeed develop into an outstanding method for the stimulation of wound healing. We produced infected injuries in rats, whose healing typically occurs in 10–12 days. In the case, the nanocarbon structures (NCS) were applied directly after the injury, and improvement and acceleration in wound healing was systematically observed (Figure 9).

The adsorption properties of carbonaceous adsorbents are used in the purification and recovery of valuable substances for very long time. Active carbons are used in oil processing, petroleum chemistry, wine making, butter production, etc. [46–48].

They are increasingly applied in medicine, for example, to remove toxins from physiological liquids [49].

Interesting approach used was the carbonization of walnut shells, grape seeds, apricot stones (AS), wheat bran, rice husk, etc. in presence of activating agents. The samples were carbonized according to the procedure developed in the R.M. Mansurova Laboratory of

Carbon Nanomaterials at the Institute of Combustion Problems, using a gas-flow setup (Figure 10) within a temperature range of 250–900 °C in argon flow (50–90 cm^{-3}·min).

Figure 9. Dynamics of infected wound healing in rats. (**A**) Nanostructured carbonized sorbents were applied after injury. (**B**) Wound healing in the control group. Reprinted with permission from Ref. [45]. Copyright 2012, IntechOpen.

Figure 10. Pilot setup for flame carbonization of diverse raw plant materials. Reprinted with permission from Ref. [45]. Copyright 2012, IntechOpen.

During carbonization, the major mass loss occurred within the temperature range of 150–500 °C, where a large amount of volatile and liquid products (65–75% of total mass) were released. In the case of rice husk, the reduction in mass was found to be around 50%, which is related to the high content of silicon in the samples.

The change in the mass of RH and AS in the process of carbonization, which was carried out in a rotating steel reactor (2 rpm) under argon flow, was studied. The process time was 60 min at temperatures between 100 and 900 °C. After heat treatment, the reactor was cooled to room temperature, purging with argon. The results are shown in Figure 11.

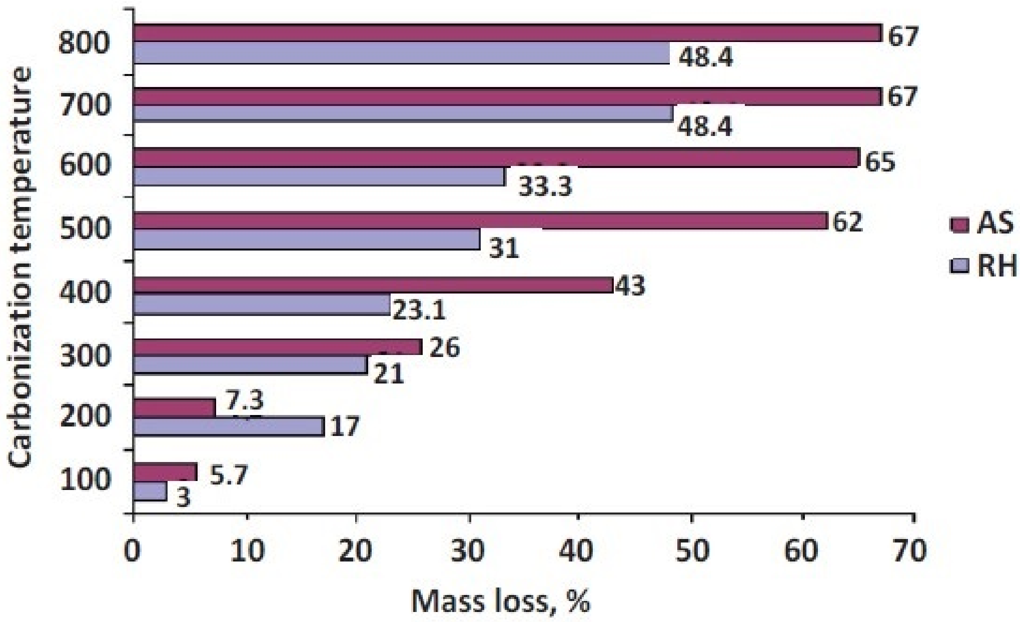


Figure 11. Dynamics of change in the mass of RH and AS in the carbonization process at various temperatures. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Beginning at 100 °C, when the mass loss for RH is 3% and 5.7% for AS, this parameter increases, and at carbonization temperature of 200 °C, it reaches 17% for RH and 7.3% for AS. As can be seen from the figure, the main mass loss occurs in the temperature range of 200 to 700 °C. When the temperature is raised up to 300 °C, the mass of the materials (RH and AS) decreases by 21% and 26%, respectively. This value is 23–43% for RH and 43–66% for AS in the temperature range from 400 to 700 °C. At 800 °C, the mass loss for RH is 48%, and for AS, it is 67%, i.e., there is a tendency to stabilize the mass of CC.

Carbon surface has a unique character. It has a porous structure, which determines its high adsorption capacity; it has a chemical composition that enables numerous interactions with both polar and nonpolar molecules. Additionally, it has active sites in the form of edges, dislocations, and discontinuities, which facilitate its chemical reactions with many compounds and functional groups. The carbonized sorbents obtained by us based on plant materials possess extended macro- and mesoporous structures, favorable for the adsorption of large molecules and cells [51–53]. One can see in Table 2 that the specific surface (S_{sp}) and size of pores increased proportionally to the carbonization temperature up to 700 °C. However, further increases in temperature caused the decrease in these parameters due to the increase in the density of the samples, as reported also by Banerjee and coworkers [53].

Electron microscopy images (Figure 12) show the meso- and macroporous structure of the materials that appeared as a result of flame carbonization. A drastic contrast is visible between the structures of the raw material and the material after temperature treatment. Interestingly, flame carbonization of the raw plant materials often led to the formation of a complex carbon nanostructure of various size and morphology. Treatment at 500 °C resulted in the appearance of transparent thin membrane sheets of 20–40 μm size. Prolonged heating (>30 min) at 600 °C caused the formed translucent films to roll into 1400 nm long tubular structures of a diameter of 400–500 nm. Further increase in the carbonization temperature and duration initiated the appearance of a variety of nanostructures of diverse morphologies.

Table 2. Specific surface and pore size of the samples carbonized at different temperatures. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Raw Material	T (°C)	Size (μm)			
		Macropores	Mesopores	Micropores	Ssp(m^2/g)
Walnut	300	25	12	1.8	250
shells	500	30	13	2.3	770
	600	30	16	2.3	780
	700	30	16	2.3	800
	800	25	14	1.7	830
	850	29	15	2.4	800
Grape	300	18	12	3	200
stones	600	22	14	6	500
	700	27	15	7	530
	800	25	13	5	540
	850	26	14	6	500

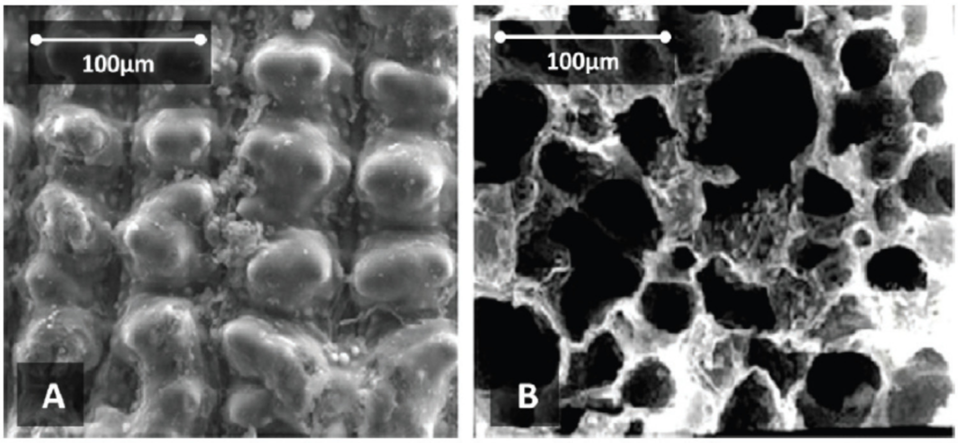


Figure 12. Electron microscopic images of rice shells in native state (**A**) and after carbonization at 650 °C (**B**). Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

The nature of the exposed chemical groups enables formation of multiple covalent bonds between the surfaces (Figure 13). The large number of different interactions involved in the cellular attachment to the carbonized surfaces makes possible fine-tuning of the immobilization process in order to achieve versatility and adaptability of the biocomposite materials for different applications [54]. Electron microscopy examinations suggested that there is strong bonding interaction between microbial cells and the NCSs. In the case of optimal incubation parameters, the cell load reaches ~62%, corresponding to ~10^8 colony-forming units (~viable cells) per gram of NCS. The microbial cells were distributed on the surfaces not homogenously but rather formed clusters (microcolonies). Taking into consideration the potential intestinal and biomedical applications of the biocomposites, this fact is of particular importance because inter-cellular interactions and aggregation processes in the micro-colonies point out the initial stages of biofilm formation, which in turn is an essential factor for bacterial survival and adaptability.

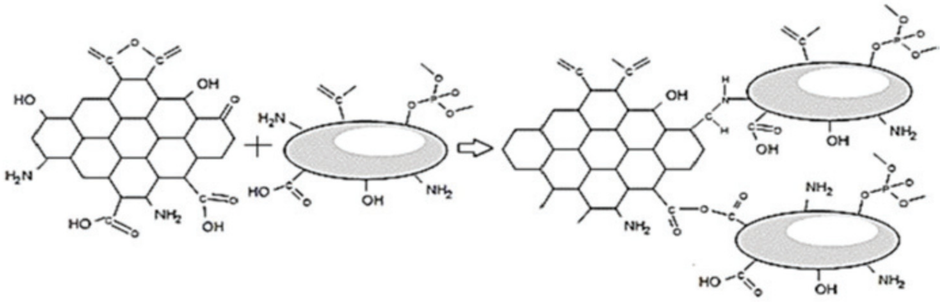


Figure 13. The formation of covalent bonds between the surfaces of microbial cells and the carbonized materials considerably contributes to the stability of the biocomposite materials. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Figure 14 shows the subsequent stages of rice husk colonization by Lactobacilli. It is clearly visible that the number of cells in a micro-colony varies between around 20 and 200, corresponding to the natural micro-colony structure in the epithelial layer of the intestine (ref). The appeared bacterial colonies demonstrated almost irreversible adhesion in the absence of a competitive substrate (intestinal surface) [55].

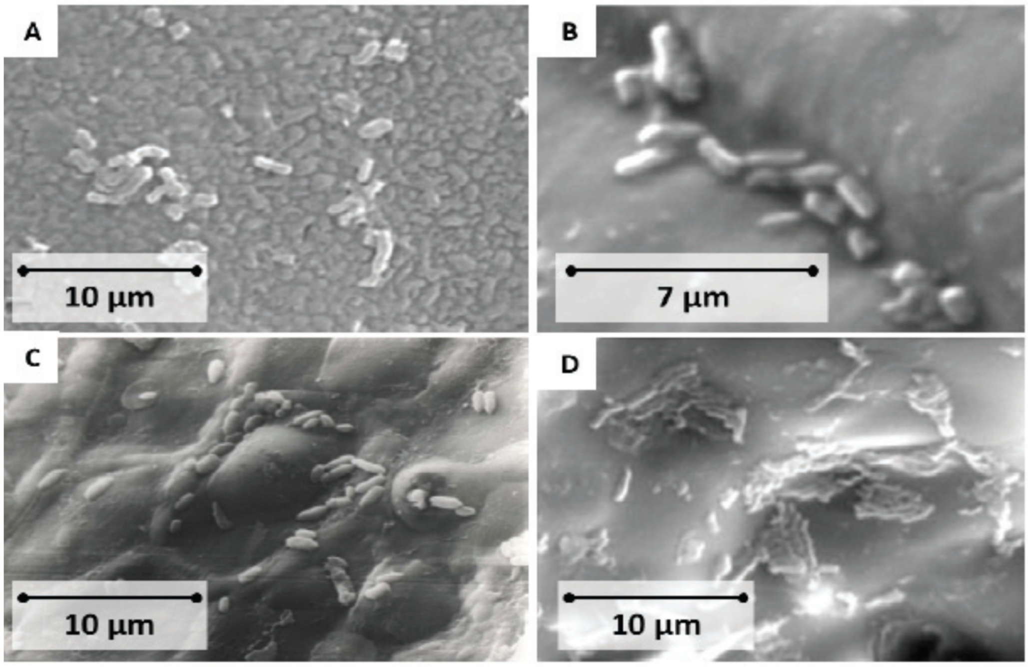


Figure 14. Subsequent stages of colonization of NCSs by Lactobacilli. (**A**) Carbonized rice husk, initial adsorption; (**B**) carbonized grape stones, initial adsorption; (**C**,**D**) carbonized grape stones and micro-colony formation (respectively). Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Thermodynamically, spontaneous cell adsorption onto a surface results in a decrease in Gibbs free energy, but sometimes there is a significant energy barrier due to electrostatic repulsion. Existing theoretical models predict that there are two regions where the strongest attraction forces between two surfaces occur (the "primary" and "secondary" minima, at distances of ~0.5 and ~5 nm, correspondingly). Generally is assumed that microbes adhere reversibly to the "secondary minimum" and irreversibly to the "primary minimum" with the aid of cell surface appendages that can pierce the repulsive energy barrier [56].

The surface properties of cells play a significant role in a number of phenomena that occur in both natural conditions and technological processes. These include the processes of coagulation and attachment of microorganisms to any surface. The protein nature of the cell wall determines the cell surface diphilicity due to the presence of both polar (hydrophilic) and non-polar (hydrophobic) groups. The adhesive properties of microorganisms determine their ability to attach to a carrier. The most important characteristic of the cell surface, which determines the adhesion of microbial cells onto the carrier, is hydrophobicity. The hydrophobic interaction takes place due to the van der Waals forces. The term "hydrophobicity" means poor surface wetting by water (or weak surface interaction with water).

In the study, 48 h cultures of yeast Rhodotorula glutinis var. glutinis isolated from wastewater and 24 h cultures of bacteria Pseudomonas aeruginosa and Pseudomonas mendocina isolated from oil-contaminated soils (Culture Collection, Microbiology Sub-Department, al-Farabi Kazakh National University) were used. For immobilization, RH and AS as raw materials with carbonization at 550, 600, 650, 700, and 750 °C were used. The results of researching the hydrophobicity of cellular surfaces are shown in Figure 15. As can be seen, on the first day, the cell hydrophobicity of all microorganisms increases sharply, and on the second day, it decreases by half, and at 96 h of cultivation, this parameter decreases to the initial values. The low value of the hydrophobicity of 12 h cultures is probably due to the fact that at the beginning of the exponential growth phase the synthesis of glycoprotein of the adhesion precursor takes place in the microbial cells.

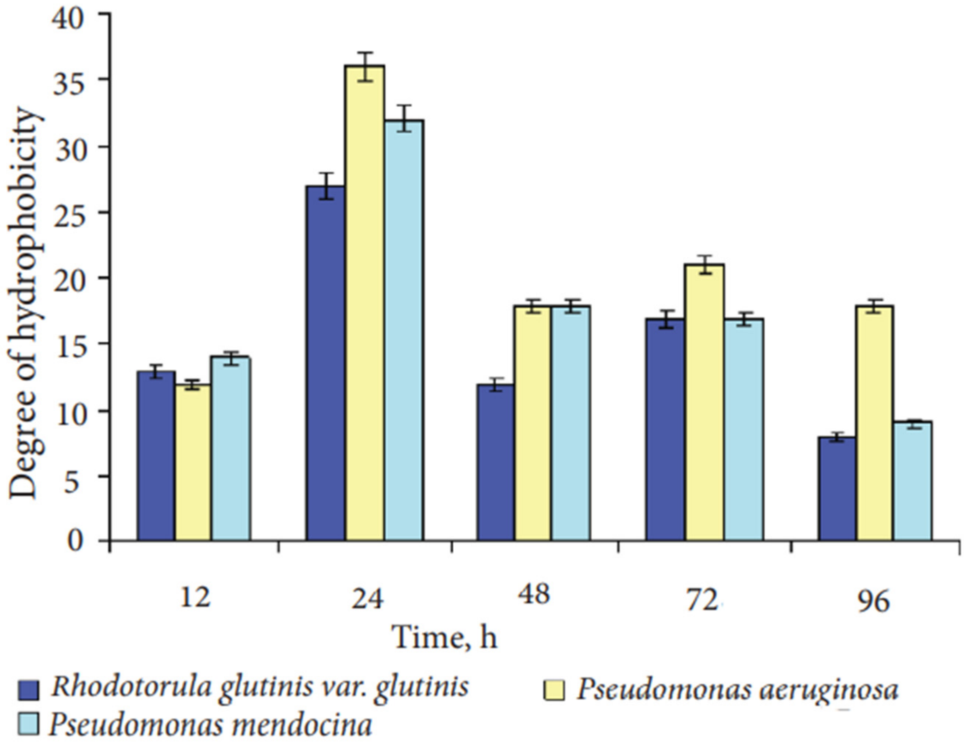


Figure 15. Changes in the hydrophobic properties of microbial cells during their cultivation on solid medium. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Figure 16a shows the attachment of yeast cells of Rhodotorula glutinis var. glutinis onto the initial and carbonized AS. It can be seen that 33% of yeast cells were sorbed onto the initial carriers. A total of 41 and 49% of yeast cells attached to the sorbents carbonized at 550 and 650 °C, respectively. Detailed characteristics of sorbents based on rice husks can be found in [50,57].

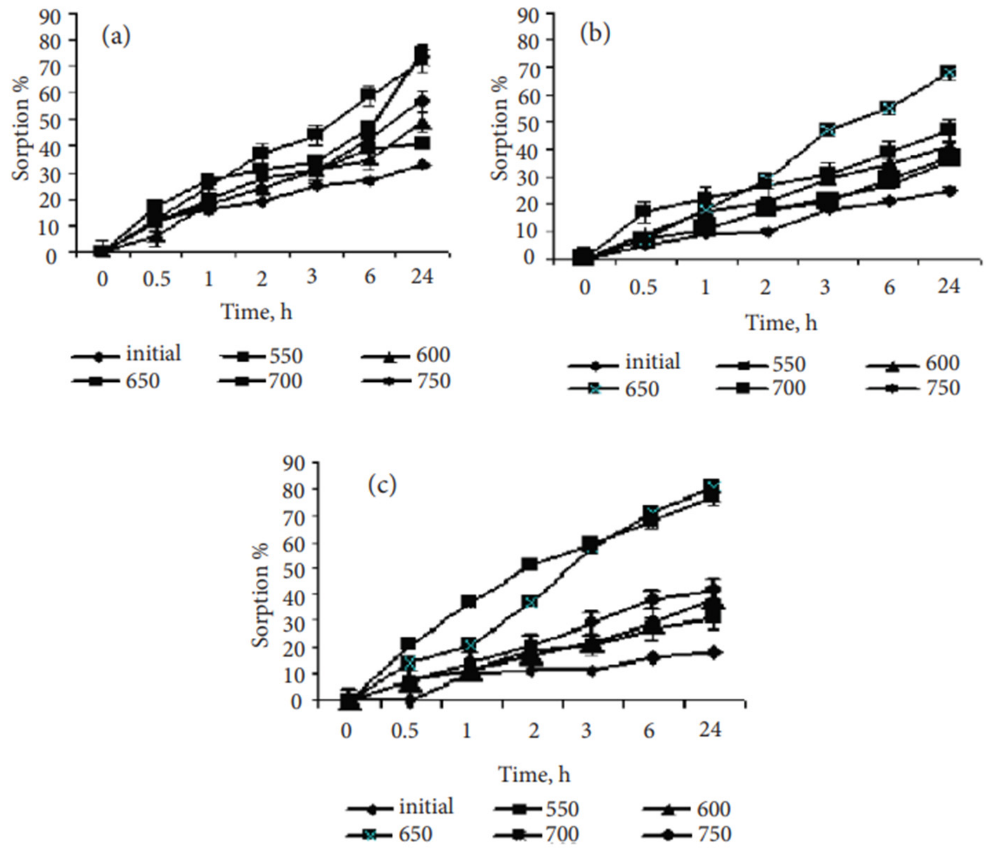


Figure 16. Dynamics of sorption of Rhodotorula glutinis var. glutinis (**a**), Pseudomonas mendocina (**b**) and Pseudomonas aeruginosa (**c**) cells onto the surface of initial and carbonized AS. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Cells attached to AS carbonized at 650 °C showed a high-percentage sorbability of 75% and 72% onto AS carbonized at 700 °C. Yeast sorption onto AS carbonized at 750 °C is 57%. The sorption of Pseudomonas mendocina cells (Figure 16b) onto the initial carrier is 25%, and 37% and 41% of cells attached onto sorbents carbonized at 550 and 600 °C, respectively. The sorption of microbial cells onto AS carbonized at 650 °C is 68% and at 700 °C is 47%. AS carbonized at 750 °C shows the lowest percentage attachment among all samples, with only 36% of the cells attached. The sorption of Pseudomonas aeruginosa cells onto the initial and carbonized AS is shown in Figure 16c. A total of 18% of microbial cells attached to the initial sorbents. It has been established that AS carbonized at 650 °C has a high sorption activity for Pseudomonas aeruginosa cells, the index is 81%, while the index for AS carbonized at 700 °C is 77%. The carriers carbonized at 550, 600, and 750 °C show low sorption indices, and the attachment percentages are 31, 38, and 42%, respectively.

The similarity of the results is likely to be largely related to the structure of CC, presence of pores, as well as chemical sorption that is caused by the interaction of the functional groups (carboxyl, carbonyl, amine, etc.) of the sorbent with microbial cells with the formation of chelate complexes. It is interesting to note that an increase in the carbonization temperature of RH leads to unequal results. The sorption of yeast cells decreases with a rise in the temperature, and the sorption of bacterial cells increases. This means that the functional groups for attachment arising from carbonization have dimensions and properties that are more specific for bacterial cells than for yeast ones.

One of the indices characterizing the attachment of microbial cells onto carriers is the cell desorption from the carriers. First, this is because only by a small (though multidot) contact region between the cell surfaces and carrier confronts the exposures causing cell detachment from the surface. In addition, the limited capacity of the carrier surface with regard to the cells is associated with a limited number of sorption sites. The data in Table 3 show the desorption of microbial cells from the surface of carbonized carriers. Thus, 19% of yeast cells attached onto the initial sample of RH, while the rate of desorption was 7%. The rate of Pseudomonas aeruginosa cell attachment was 20%, with a desorption rate of 19%. The sorption of the same cells onto RH carbonized at 650 °C reached 68%, and desorption 6.8%; 33% of Rhodotorula glutinis var glutinis cells attached onto the initial AS, and the desorption rate was 9.5%. The rate of Pseudomonas aeruginosa cells attachment onto AS carbonized at 650 °C was 81%, with a rate of desorption of 7.5%. As a result of the conducted experiments, it was found that the desorption rate for the cells attached to materials carbonized at 650 °C is much higher compared with the data obtained for other sorbents.

Table 3. Sorption and desorption of microbial cells from carbonized carriers. Reprinted with permission from Ref. [50]. Copyright 2020, Jenny Stanford Publishing Pte. Ltd.

Cultures	**Initial RH**		**RH at 650 °C**		**Initial AS**		**AS at 650 °C**	
	Sorption (%)	**Desorption (%)**	**Sorption (%)**	**Desorption (%)**	**Sorption (%)**	**Desorption (%)**	**Sorption (%)**	**Desorption (%)**
Rhodotorula glutinis var. Glutinis	19	7	64	6.3	33	9.5	72	5.5
Pseudomonas aeruginosa	20	19	68	6.8	18	11	81	7.5
Pseudomonas mendocina	29	12	47	5.7	25	14	68	8.4

The cell wall structure is much more complicated in Gram-negative bacteria than that of Gram-positive bacteria. It includes a much larger number of macromolecules of different chemical types. Peptidoglycan forms only the inner layer of the cell wall, loosely adhering to the cytoplasmic membrane. The content of this heteropolymer varies widely in different species of Gram-negative bacteria. In most species, it forms a one- or two-layer structure characterized by very rare transverse bonds between heteropolymer chains. Peptidoglycan structural units comprise N-acetylglucosamine residues interconnected in cellulose through 1, 4-glucosidic bonds [50].

Carbon nanomaterials, as the most promising materials of the 21st century, are among the most current and intensively researched areas. Rice husks are also a good source for carbon nanomaterials. The book [58] published under the editorship of Z.A. Mansurov collected advanced results on the obtaining and application of carbon nanomaterials in biomedicine and the environment, including those obtained by processing rice husks. The book considers issues of obtaining biocomposites, porous carbon nanostructured sorbents, including those for fusicoccin extraction and blood purification.

4. Conclusions

In this work, certain achievements in the effective processing of rice husks with further application in biotechnology and medicine were collected. It has shown that all components that can be extracted from rice husk are suitable and of extraordinary value as biomaterials.

Biotechnological uses of rice husks include, but are not limited to, bioplastics, biocatalyst media, butanediol production, animal feed, biogas, biochar, biochar, compost, cellulose production, food packaging, and liquid fuel.

The medical applications of RH products include, but are not limited to, the following areas: production of biocompatible SiO_2, including medical glass, production of cellulose for medical applications, for protein extraction, and also a great director is the production of carbon nanomaterials for various sorption processes and even for wound healing. The purpose of this work was to demonstrate the versatility of the use of materials from rice husks. This work perfectly demonstrates that rice husks can be processed without any residual components and, in parallel, solves problems with the valorization of biomass.

In conclusion, rice husks and their derivatives are cheaper and more accessible than other vegetable wastes. Rice husks are one of the most popular materials for solving problems in biotechnology and in medicine, especially in the treatment of cancer.

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