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Research of Carbon Biosensors for Application in Seating Furniture: A Review

Istraživanje ugljičnih biosenzora radi primjene u namještaju za sjedenje – pregled literature

REVIEW PAPER
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ABSTRACT • *The paper provides a limited overview of existing pressure sensors based on composite technology from carbonized biomass and synthetic materials which could be implemented in seating furniture. Carbon-based pressure sensors have proven to be good for pressure measurement that works on the principle of the piezoresistive effect. Research on materials based on carbonized components of biological origin encourages the development of composite sensors made of different materials, which have different negative and positive properties. Despite the great potential, such sensors are still not sufficiently researched and there is a lot of space for their improvement. Today's rapid development of technologies and frequent work at the computer leads to excessive sitting while working, which is a big problem for human health. Chairs with sensors could be increasingly used in the future, and in combination with the Internet of Things could be used to monitor the sitting habits and health of users. Sensors implemented in seating furniture are one way of monitoring sitting habits, warning users of inappropriate body positions when sitting, and mitigating the negative consequences of long-term improper sitting. The paper analyses research that includes the production and application of sensors made of carbonized bio-materials, which could be used in seating furniture with the aim of monitoring the way of sitting based on the principle of pressure detection. So far, the results have not provided the requested answers. However, they provided an overview of technologies that, with additional research, likely have the potential to be incorporated into seating furniture.*

KEY WORDS: *carbonized biomaterials, biosensors, seating furniture, smart seating, health*

SAŽETAK • *Rad donosi ograničen pregled postojećih senzora tlaka utemeljenih na tehnologiji kompozita od karbonizirane biomase i sintetskih materijala koji bi se mogli implementirati u namještaj za sjedenje. Senzori tlaka na bazi ugljika pokazali su se dobrima za mjerenje tlaka na načelu piezootporničkog učinka. Istraživanja materijala na bazi karboniziranih komponenata biološkog podrijetla potiču razvoj kompozitnih senzora od različitih materijala koji imaju negativna i pozitivna svojstva. Unatoč velikom potencijalu, takvi senzori još nisu dovoljno istraženi te postoji mnogo prostora za njihovo unaprjeđenje. Današnji brzi razvoj tehnologija i dugotrajan rad za računalom rezultiraju prekomjernim sjedenjem pri radu, što je velik problem za čovjekovo zdravlje. Stolice sa senzorima u budućnosti bi mogle naći sve veću primjenu, a u kombinaciji s mrežnom strukturom Internet stvari mogle bi se iskoristiti za praćenje navika sjedenja i zdravlja korisnika. Senzori implementirani u namještaj za sjedenje jedan*

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su od načina praćenja navika sjedenja, upozoravanja korisnika na neodgovarajuće položaje tijela pri sjedenju i za ublažavanje negativnih posljedica dugotrajnoga nepravilnog sjedenja. U radu su analizirana istraživanja koja obuhvaćaju izradu i primjenu senzora od karboniziranih biomaterijala koji bi mogli naći primjenu u namještaju za sjedenje radi praćenja načina sjedenja na načelu detektiranja tlakova. Rezultati zasad nisu dali tražene odgovore. Međutim, dali su pregled tehnologija koje uz dodatna istraživanja vjerojatno imaju potencijala za primjenu u namještaju za sjedenje.

KLJUČNE RIJEČI: *karbonizirani biomaterijali, biosenzori, namještaj za sjedenje, pametno sjedenje, zdravlje*

1 INTRODUCTION
1. UVOD

It is a time of exponential development of technology and frequent work on the computer, where excessive sitting is a big problem for human health (Oven *et al.*, 2010). Chairs with sensors will be in increasing use, which, in combination with the Internet of Things, can be put to good use in monitoring the habits and health of users, and thus in the prevention of potential diseases.

Piezoresistive pressure sensors have attracted great interest from scientists in today's time of exponential technological development (Tai *et al.,* 2022). Their potential application is present in the development of the latest technologies such as wearable electronics or intelligent systems like robotic sensors, electronic skin, systems for monitoring movement or monitoring physiological information of the human organism (Lei *et al.,* 2022; Zhang *et al.,* 2019). Carbon-based composite pressure sensors have proven to be an excellent means of pressure measurement that functions on the principle of piezoresistive effect (Huang *et al.,* 2017).

The piezoresistive effect represents a change in the electrical resistance of a material (e.g. semiconductor or metal) under mechanical stress. The change in resistance occurs due to a change in the geometry (crystal lattice) and electrical conductivity of the material. It is significantly higher in semiconductors than in metals. Piezoresistive sensors based on silicon semiconductors are commonly used. In such an example, four Si-resistors are pressed into the semiconductor membrane and connected in a Wheatstone bridge. Under the influence of pressure, the diaphragm deforms, thereby changing the electrical resistance of the four resistors. The change in resistance is proportional to the applied pressure. This means that the voltage difference across the Wheatstone bridge is proportional to the applied pressure (Bolf, 2019; Tran *et al.,* 2018).

Various materials based on carbonized components of biological origin have been researched by many authors, and composite sensors made of different materials have been developed based on their findings. Each of them shows different negative and positive properties. Despite the great potential, such sensors are still not sufficiently researched and there is a lot of space for their improvement. Therefore, scientists devoted themselves to finding a suitable material that would adequately replace expensive and non-renewable materials (Bartoli *et al.,* 2022; Liu *et al.,* 2018; Mishra *et al.,* 2021). Given that the search for an ideal material emphasizes naturally renewable, ecological and cheap materials, carbon-rich carbonized biomass was found at the center of the research. In order to produce a high-quality sensor of this type, it is necessary to design a composite material that will be extremely sensitive, long-lasting and stable in different conditions. The functioning of this type of sensor can be influenced by numerous material factors such as electrical conductivity, mechanical properties, stability in different conditions and the range of pressure sensitivity.

When talking about the use of these sensors in furniture, negative properties can be weak flexibility, insufficient sensitivity at relatively low pressures, permanent deformation and low repeatability. Positive properties would be the design of the sensor for working at lower pressures, suitable for those that occur when sitting, then great durability and linear characteristics.

Wood is the most available renewable resource and offers a sustainable solution for making lightweight carbonized materials (Chen, Z. *et al.,* 2020). In modern technology, pressure sensors must often have high sensitivity and a wide linear range. However, there are few who can meet both criteria. The active material of the sensor would have to have a rough surface so that the electrode can respond sensitively to pressure changes. In addition, such a material would have to withstand a high degree of deformation, i.e. maintain good sensitivity in a large pressure range (Huang *et al.,* 2018). Natural wood has a unique 3D microstructure that implies a hierarchy of interconnected channels along its growth direction. Lignin is the most abundant aromatic substance on Earth, and at the same time it is cheap, renewable, environmentally friendly, and available. Carbonized lignin as a conductive component is a suitable material for making a flexible composite with polydimethylsiloxane (PDMS) as a polymer matrix (Wang *et al.,* 2018). Similar to the occurrence of lignin, cellulose is the most common renewable biopolymer (also sustainable, biocompatible, and biodegradable) on Earth, which is mainly obtained from cotton and lignocellulosic biomass (most often wood or grass). For example, sensors based on cellulose paper are increasingly used in "green" electronics due to their wide distribution, low cost, light weight, and excellent flexibility and sustainability (Chen *et al.,* 2018). Lignin and cellulose are suitable components for creating aerogel – a porous material of low density (contains more than 90 % air), which can have excellent mechanical properties, high compressibility, resistance to material fatigue and excellent sensitivity in a wide range of working pressure. Chen *et al.* (2020) investigated an aerogel based on flexible cellulose nanofibers (CNF) connected in a 3D network. In the network created in this way, alkali-lignin (obtained by the alkaline process of cooking cellulose) with its high thermal stability reduces thermal deformation, thus creating a very stable structure.

Light and elastic carbon materials, thanks to their outstanding properties, represent one of the most important candidates for the development of high-performance flexible sensors. In the last few years, a number of carbon materials with low density and high porosity have been synthesized from nanocarbon, such as graphene, graphene oxide, carbon nanotubes (CNT) or their composites. The carbon materials obtained in this way show good mechanical properties, which implies elasticity, and in addition, they have exceptional electrical properties and as such are suitable for making sensors in the increasingly common so-called wearable technology. However, they are non-renewable, and the process of their production is expensive and complex (Chen *et al.,* 2020). Often, when making flexible pressure sensors, materials such as polyurethane (PU) foams and melamine-formaldehyde (MF) foams are used; however, they are also not environmentally friendly due to the way they are manufactured (Li *et al.,* 2021).

On the other hand, biochar can be a good solution for the conductive sensor component due to its ease of production, low cost, and positive attitude towards the environment. However, not every biochar has electrical conductivity, and it depends on many factors. Some of these factors are the mass fraction and density of the powdered carbonized material in the composite, or the pyrolysis temperature in the carbonization process of biomaterials. Marrot *et al.* (2022) obtained results in which the conductivity test showed that pyrolysis at higher temperatures results in higher conductivity of biochar particles at the desired pressure or density of the compacted biochar particles. Understudied electrical conductivity of biochar in composite materials may be a potential for innovation in this area. In addition, polyvinyl alcohol has numerous advantages such as easy processing, high durability, low price, non-toxicity, and favorable insulating properties (Nan and DeVallance, 2017). Noori *et al.* (2020) state that the production of tea is one of the largest productions of beverages in the world. By preparing tea in the extraction process, only a small number of compounds are removed, and a large amount of usable residue remains, which can be used for the purpose of making biochar. Global rice production is increasing to keep pace with the growing global population as well. Rice husk is a by-product in the production of rice, which is obtained by peeling the grain. According to Haffiz *et al.* (2017), rice husk is a cheap and sustainable solution for making a conductive pressure sensor component. Such a conductive component in combination with PDMS forms the active part of the sensor. In recent years, pressure sensors made of carbonized fabric have appeared; they are characterized by excellent flexibility and pressure reading, as well as ease of preparation and low cost. Given that fabrics in the sensor function are still insufficiently researched, Chang *et al.* (2020) investigated a flexible sensor based on carbonized cotton fabric and thermoplastic polyurethane (TPU).

The aim of this paper is to present different types of existing pressure sensors made of carbonized components obtained from biomass, with an emphasis on sensors that have the potential to be installed in seating furniture with the purpose of monitoring the way of sitting based on the principle of pressure detection.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Data for this research was collected from databases of scientific articles with open access from several fields of science (technical and biotechnical, biomedical and health, and natural sciences).

The keywords for the database search were: "biochar pressure sensor" and "carbonized pressure sensor". Databases (such as IEEE Xplore, ACS Publications, ScienceDirect, SpringerLink) were searched during June and July 2022, and included papers published in the last five years (2017-2022). Papers that included sensors made of carbonized organic materials were selected. Papers related to strain sensors were excluded from the overview, as well as papers with pressure sensors in which the combination of conductive component material and resin matrix material (carrier) was repeated.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The analysis of pressure sensors based on a carbonized component of organic origin found that there are different types of sensors, but they all have a common feature of working on the principle of piezoresistive effect. Most of them were developed for the purpose of use in wearable devices, i.e. robotic skin or devices for monitoring biosignals in humans.

The manufacturing method and methods of researching their properties can be found in the original articles of the cited authors, while here is a presentation of basic details and results that can be interesting guidelines for future research and application in seating furniture.

3.1 Biochar sensor of wood origin and polyvinyl alcohol
3.1. Senzor od biougljena drvnog podrijetla i polivinil alkohola

Polymer composites based on electroconductive carbon are considered acceptable materials for pressure and strain sensors based on the piezoresistive principle of operation. Nan and DeVallance (2017) investigated the responses of a pressure sensor as a composite material obtained from a mixture of hardwood biochar and polyvinyl alcohol (PVA). The produced composite PVA/biochar sensors showed piezoresistive properties under pressure. It was observed that, as the biochar content changed within sensor, the electrical response also changed proportionally, i.e. by increasing the proportion of biochar from 8 wt% to 12 wt%, the output voltage increased, as the sensor was subjected to increasing pressure. However, in such situations, one should be careful, because a further increase in the proportion of the substance does not necessarily lead to an improvement in the properties of the sensor, but on the contrary, it may reach a threshold when the sensor becomes unusable. Furthermore, with increasing pressure, the resistance of the PVA/biochar composite sensor gradually decreased. The effect of composite thickness was found to be important, but also complex, as many factors, such as biochar particle size, their amount and spatial distribution, and the electrical and mechanical properties of the PVA/biochar films likely influenced the results. In addition, temperature can affect the electrical response and piezoresistive effect of the PVA/biochar sensor. However, the research results showed that in the temperature range from 25 to 70 °C the sensors were relatively stable. The research showed that there is a basis for further research on the influence of particle size and conductivity properties of biochar, because the electrical response and piezoresistive behavior of polymer materials filled with biochar and carbonized wood material are repeatable and stable.

3.2 Biochar sensor made of tea origin and polypropylene
3.2. Senzor od biougljena čajnog podrijetla i polipropilena

Noori *et al.* (2020) investigated a composite material based on biochar obtained from exhausted tea leaves and polypropylene. The developed biochar samples proved to be poorly conductive up to low temperatures. A produced powder was dispersed in a polypropylene matrix up to a load of 40 wt%, and a noteworthy conductivity was obtained (Figure 1). However, at such a high level of biochar content, after the initial increase in conductivity, applied pressures above a certain point no longer result in different electrical outputs, which is why the sensors can only be useful for detecting the presence of pressure, but not their values.

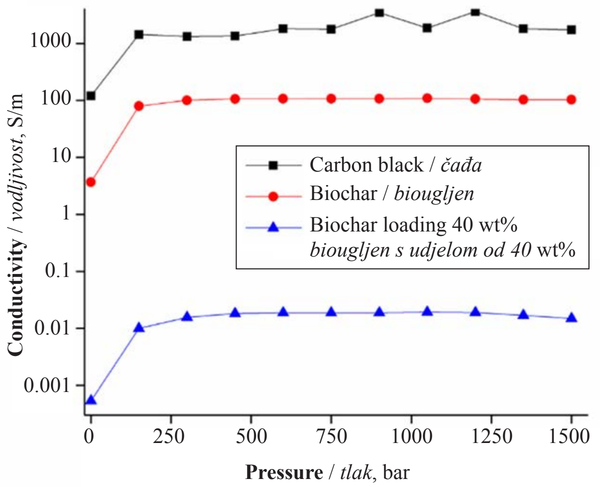

Figure 1 Electrical conductivity as a function of pressure on fillers and biochar with a loading of 40 wt%, carbon black and tea biochar (Noori *et al.,* 2020)
Slika 1. Električna vodljivost kao funkcija pritiska na punila i biougljen s udjelom od 40 wt%, na čađu i biougljen čaja (Noori *et al*., 2020.)

The properties of the produced materials were determined in detail by testing mechanical, thermal, morphological, and electrical characteristics in relation to temperature. The material showed a general improvement in mechanical and thermal properties when the amount of filler was varied instead of the type of filler, as similar concentrations of carbon black and biochar caused similar effects. Electrical conductivity was also studied for a large range of pressures, when the sensor underwent plastic deformation. An increase in conductivity by a whole order of magnitude was observed in the case of biochar loading of 40 wt%. This phenomenon occurs together with plastic deformation, effectively acting as an irreversible overpressure detector. The researched technology could find application in various areas where it would serve as a sensor to detect irregularities due to, for example, impact.

3.3 Biocarbon sensor from cellulose fibers
3.3. Biougljični senzor od celuloznih vlakana

According to Li *et al.* (2021), it is a major challenge to fabricate compressible aerogels for flexible pressure sensors from cellulose-based materials in an environmentally and cost-effective manner. Carbonized cellulose fiber network (CCFN) and polydopamine (PDA) are materials for a flexible pressure sensor

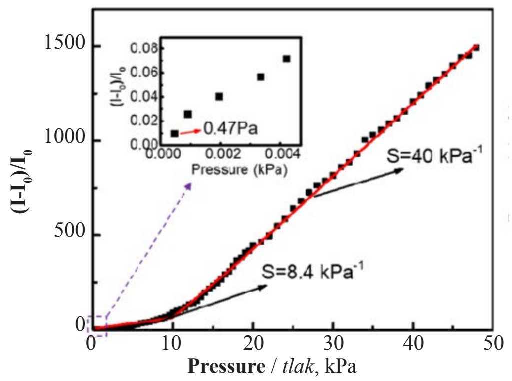

Figure 2 Relative change in electrical current $[(I-I_0)/I_0]$ as a function of pressure ranging from 0 to 50 kPa in PDA/CCFN-based pressure sensor (Reprinted (adapted) with permission from Li *et al.* Copyright 2021 American Chemical Society)
Slika 2. Relativna promjena električne struje $[(I-I_0)/I_0]$ kao funkcija tlaka u rasponu od 0 do 50 kPa u PDA/CCFN senzoru tlaka (preuzeto s dozvolom iz Li *et al.*, Copyright 2021 American Chemical Society)

obtained in a low-cost, scalable, and environmentally friendly process. This process gives the prepared pressure sensor high compressibility and excellent mechanical durability.

The pressure sensor based on PDA/CCFN has a high sensitivity of 8 kPa^{-1} and 40 kPa^{-1} at pressure ranges of 0–10 kPa and 10–50 kPa, respectively (Figure 2). The sensor has a detection limit of less than 0.5 Pa, a fast response time (for a pressure of 50 Pa: 50 ms and 20 ms for loading and unloading, respectively), and a very good repeatability of 1000 cycles (for a pressure of 20 kPa). The excellent properties of this kind of sensor enable accurate recognition of various human actions, it can monitor fine biomedical signals in humans and more. The development of a flexible cellulose fiber pressure sensor that can be used to map the pressure distribution or as a pixel detector to detect spatially resolved pressure is a new viable approach in fabrication for applications in electronic skin and wearable electronics; however, due to its high sensitivity, it is not applicable in seating furniture.

3.4 Carbonized wood sensor with polydimethylsiloxane filling
3.4. Senzor od karboniziranog drva s punilom od polidimetilsiloksana

Huang *et al.* (2018) developed a simple procedure for the fabrication of flexible pressure sensors based on carbon using natural wood structures and silicon. The method they developed uses a blade cutting process in a unique multi-channel composite structure with variable surface topography. The authors studied the role of carbon surface microstructures in the pressure sensor by using horizontally and vertically cut composite layers in a vertical piezoresistor configuration.

Due to their rough surface and highly deformable microstructure, the horizontally cut composite sensors exhibit much higher sensitivity and a wider linear range, while exhibiting low hysteresis and good cycle stability. The wide linear range is an outstanding property that enables the sensor to precisely track human physiological signals (e.g. real-time breathing detection), and the high sensitivity property is suitable for measuring epidermal pulse, for example.

3.5 Carbonized lignin sensor from corn and polydimethylsiloxane
3.5. Senzor od karboniziranog lignina iz kukuruza i polidimetilsiloksana

Wang *et al.* (2018) presented a flexible composite of polydimethylsiloxane and carbonized lignin (PDMS/CL) that is electrically highly sensitive and was made by a simple and inexpensive process. The conductivity of the PDMS/CL composite with one-third part of carbonized lignin is at least 16 times lower than the conductivity of the obtained CL, whose oxygen and hydrogen content were drastically reduced during the simple carbonization process. A relative change in resistance response, built up during an applied stress of 0 to 20 kPa, was found in the pressure-sensitive phase in the range of 0 to 3 kPa. Previous reports on transistor pressure sensors and most other carbon materials sensors indicate significantly lower sensitivity than the 57 kPa^{-1} achieved here, which is very interesting.

The PDMS/CL composite shows excellent and stable pressure frequency response of up to 2.5 Hz. At the same time, the time of response to loading is approximately 60 ms, while the response to unloading occurs in 40 ms. The sensor has exceptional durability, which is manifested by the intensity of the response to repeated compression, which is stable for as many as 100,000 cycles. The paper proved the possible application of lignin in the production of flexible sensors in a relatively cheap process, with good reproducibility and high sensitivity that finds application in wearable electronics (for example, pulse monitoring by delicate pressure changes or muscle movements) and smart systems where force is demanded.

3.6 Biocarbon sensor from rice husk and polydimethylsiloxane
3.6. Biougljični senzor iz rižine ljuske i polidimetilsiloksana

By using the pyrolysis of plant biomass, biochar is obtained, which can be considered as an alternative source of "green" carbon for the production of pressure sensors based on polymer foams, according to Haffiz *et al.* (2017). In the paper, foams produced by the sugar template method were studied, while biochar obtained by pyrolysis of rice husk in the extraction of liquid fuel was explored as a filler. By static and cyclic loading of a sensor device with biochar/PDMS foam between two copper electrodes, the properties of the pressure sensor were investigated, and the mechanical characteristics were also studied. Tests have shown an inversely proportional relationship between electrical resistance and pressure increase, whereby the biochar/PDMS foams produced in this way show a negative pressure resistance coefficient.

The sensor showed remarkable electrical conductivity, which increased significantly during compression. Mechanical properties during compression showed that this sensor behaves like a typical elastomeric foam. Hysteresis is present during the loading and unloading cycles. The response is in the elastic region during lower stresses with a trend of a slight increase due to the action of higher stresses, and then a sudden increase in deformation at higher stresses. This leads to the fusion of opposite cell walls and a drop in electrical resistance, and an increase in conductivity.

3.7 Sensor made of cellulose nanofibers and lignin
3.7. Senzor od celuloznih nanovlakana i lignina

Fabrication of wood-derived elastic carbon aerogel with a tracheid-like texture from cellulose nanofibers (CNF) and lignin is a sustainable and simple method presented by Chen *et al.* (2020). Carbon aerogel obtained from wood shows high durability and compressibility, which are excellent mechanical properties. In addition, it has high sensitivity in a wide range of working pressure up to 17 kPa, which enables precise detection of human biosignals.

A flexible, free-standing symmetric solid-state supercapacitor can be made of carbon aerogel, which shows satisfactory results for applications in pressure sensors and flexible electrodes with its electrochemical properties and mechanical flexibility.

3.8 Carbonized cotton fabric sensor with thermoplastic polyurethane
3.8. Senzor od karbonizirane pamučne tkanine s termoplastičnim poliuretanom

By a simple carbonization process, Chang *et al.* (2020) made an elastic pressure sensor based on fabric and thermoplastic polyurethane (TPU). The influence of carbonization temperature variations (up to 1000 °C) and the concentration of the flexible substrate solution (up to 10 %) on the properties of the sensor was investigated, which was confirmed by tests under different process conditions. After research, it was determined that the pressure sensor made in this way, with fabric carbonized at a temperature between 800 and 900 °C and with a concentration of 6 % thermoplastic polyurethane, has a sensitivity of up to 80 kPa^{-1} (at pressure of 0.5 kPa) and a hysteresis of less than 12 %, which unfortunately does not make it a candidate for use in furniture, but is therefore excellent for use in wearable electronics.

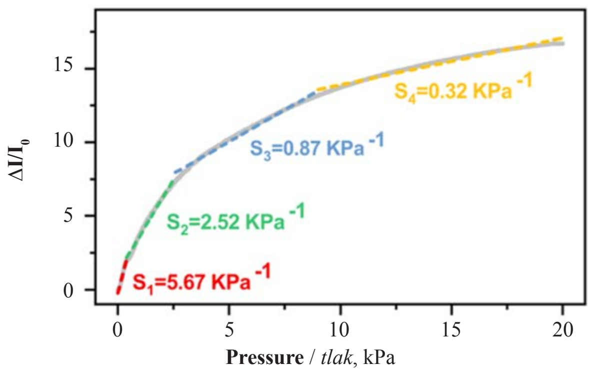

Figure 3 CCP pressure sensor sensitivity shown as relative change in electric current under pressure load (Reprinted (adapted) with permission from Chen *et al.* Copyright 2018 American Chemical Society)
Slika 3. Osjetljivost CCP senzora tlaka prikazana kao relativna promjena električne struje pod tlačnim opterećenjem (preuzeto s dozvolom iz Chen *et al.*, Copyright 2018 American Chemical Society)

3.9 Sensor made of carbonized crepe paper with a wavy structure
3.9. Senzor od karboniziranog krep-papira valovite strukture

Taking advantage of the porous and corrugated structure of carbonized crepe paper, Chen *et al.* (2018) developed a flexible pressure sensor. The sensor is based on a simple and scalable approach, using screen-printed interdigital electrodes on printing cellulose paper and carbonized crepe paper (CCP). The presented sensor has very good electromechanical properties, including high sensitivity, wide operating pressure range up to 20 kPa (Figure 3), fast response time (less than 30 ms), low detection limit of only 0.9 Pa, and durability greater than 3000 cycles.

The advantages of carbonized crepe paper pressure sensors, according to authors, are flexible substrate and active component (printing paper and crepe paper, respectively), having a microstructure that can be adapted to known papermaking technologies, in order to meet different requirements: simple, scalable, cost-effective and environmentally friendly, produced in the process and, due to the origin of the components, available at a low price and in sufficient quantities. The mentioned advantages enable the sensor to detect pressure changes, for example, caused by the pulse on the hand, breathing, speech, etc., but also to monitor the spatial distribution of pressure in real time. This sensor, like most of the previously described ones, has potential applications in wearable electronics, robotics, healthcare and human-machine interface.

3.10 Discussion
3.10. Rasprava

The basic difference between the described sensors is in the materials and manufacturing process. According to the materials used to make the conductive component, sensors can be from: carbonized wood and wood substances (lignin, cellulose fibers); carbonized extracted tea leaf; carbonized lignin from corn; carbonized rice flakes; carbonized cotton fabrics; and carbonized crepe paper. The conductive components of all described sensors are made of organic biomass. Considering the growing environmental awareness, the conductive elements of all described sensors can be made from biological waste or excess unused material (residue) from production.

Carbonized organic mass can have excellent electrical conductivity properties, but poor mechanical properties, which is solved by adding conductive material in carrier from different types of synthesized materials. The following polymer matrix materials are usually used as a carrier: polyvinyl alcohol (PVA); polypropylene (PP); polydimethylsiloxane (PDMS); thermoplastic polyurethane (TPU); and polydopamine (PDA).

All described sensors, except for one, are characterized by more or less elastic properties with different changes in electric resistance. In many results presented, the usefulness and operating range of the sensor are partially dependent on the matrix material. Unlike the others, the sensor based on polypropylene matrix is specific in a way that it showed irreversible plastic deformation. It seems that the PP was the reason for the non-reversibility, due to its higher plastic phase than in common epoxy resins, and as a counterexample to the excellent flexibility of the PVA polymer matrix material in one of the papers presented. Such an irreversible pressure sensor could also find application in many sectors, e.g. a sensor for detecting a local shock-induced failure.

All processed papers on “biochar pressure sensor” or “carbonized pressure sensor” are shown in Table 1, where an overview of the used conductive component material, matrix material, sensitivity, operating range, and other summary data are given.

The sensor based on carbonized cotton fabric with TPU matrix showed the best sensitivity (80.59 kPa^{-1}). Despite the excellent sensitivity, this sensor has relatively poor durability, i.e. repeatability (endurance) of only 4,000 cycles. The second most sensitive sensor was the one made of carbonized corn lignin and PDMS matrix. It showed a sensitivity of 57 kPa^{-1} and an exceptional repeatability of 100,000 cycles. In addition, the working range of this sensor is above average high, up to 130 kPa. The sensor made of carbonized wood and carrier with PVA has a maximum working range of 0 to 358 kPa. The sensor made of carbonized wood and PDMS showed the highest response speed, lasting 20 ms for loading and the same amount for unloading. According to these data, it is noticeable that all conductive materials are made using different technologies and different processes (carbonization time, temperature, conditions). The processing method to make biocarbon or biochar (i.e. filler) is an important factor in determining the appropriateness of the material used in a sensor.

PDMS seems to be the most suitable matrix material, as it is characterized by high sensitivity, working range, response speed and repeatability. However, according to Ariati *et al.* (2021), the main disadvantage of PDMS is its structural application, which may be extremely specific and reduced. However, the modification of its characteristics, such as transparency, can be interesting for the use in sensors and for some other application. It is also limited by the lack of (covalent) bonds between PDMS and surface modifiers, which lead to the loss of modifiers (Miranda *et al.,* 2022). Given that the positive properties of PDMS are expressed in different sensors, it is necessary to analyze in more detail the correlations between the composite manufacturing procedures and the quantity and quality of the materials used.

According to the mentioned properties and analyses, sensors based on carbonized biomass have great potential for implementation in cutting-edge technological discoveries such as robotic skin and wearable devices for monitoring physiological information in humans. Apart from the previously described purposes of the analyzed sensors, none of the above should be understood as a means of measuring the pressure load in the use of furniture.

In order to have the potential to be used in e.g. seating furniture, the solutions presented here should be developed in such a way as to improve the design of the sensor, which would be a combination of the best known properties. Such sensors do not have to be super-sensitive like those on wearable devices, but they must be robust: be durable enough, have the minimum necessary elasticity, have the best sensitivity in the area of pressures that occur in the given circumstances (e.g. under the sitting bones and surrounding tissue when sitting), have a relatively fast response, be discreet. These would be the parameters that determine the properties of the sensor, as well as the necessity of a simple interface and connectivity with existing devices for displaying output signals.

4 CONCLUSIONS
4. ZAKLJUČAK

In today’s time of exponential development of technology and frequent work on the computer, excessive sitting is a big problem for human health. Chairs with sensors will be increasingly used, which in combination with the Internet of Things can be put to good

Table 1 Comparison of properties of analyzed pressure sensors
Tablica 1. Usporedba svojstava analiziranih senzora tlaka

Paper *Članak*	**Conductive component material (filler)** *Materijal vodljive komponente (punilo)*	**Filler percentage** *Udio punila*	**Resin matrix material** *Smolasti materijal matrice*	**Sensor dimensions** *Dimenzije senzora*	**Biochar preparation parameters** *Parametri pripreme biougljena*	**Sensitivity** *Osjetljivost,* kPa^{-1}	**Operating range** *Radni raspon,* kPa	**Response speed** *Brzina odaziva,* ms	**Repeatability, no. of cycles** *Ponovljivost, broj ciklusa*
Nan and DeVallance (2017)	carbonized wood *karbonizirano drvo*	8 wt%, 10 wt% and 12 wt%	polyvinyl alcohol *polivinilni alkohol*	(D8×0.5 mm^3)	n/a	n/a	< 358	n/a	n/a
Noori *et al.* (2020)	carbonized extracted tea leaves *karbonizirani listovi ekstrahiranog čaja*	40 wt%	polypropylene *polipropilen*	(6×30×1.0 mm^3)	1000 °C / 30 min	n/a	n/a	n/a	n/a
Li *et al.* (2021)	carbonized cellulose fibers *karbonizirana celulozna vlakna*	23.5 wt%	polydopamine *polidopamin*	n/a	800 °C / 3 h	40	< 50	loaded / *opterećen*: 50 unloaded / *neopterećen*: 20	1,000
Huang *et al.* (2018)	carbonized wood *karbonizirano drvo*	approx. 9 wt%	polydimethyl-siloxane *polidimetil-siloksan*	(3×3×0.5 mm^3)	800 °C	10.74	< 100	loaded / *opterećen*: 20 unloaded / *neopterećen*: 20	13,000
Wang *et al.* (2018)	carbonized lignin from corn *karbonizirani lignin iz kukuruza*	33.3 wt%	polydimethyl-siloxane *polidimetil-siloksan*	(10×10×1.0 mm^3)	900 °C / 2 h	57	< 130	loaded / *opterećen*: 60 unloaded / *neopterećen*: 40	100,000
Haffiz *et al.* (2017)	carbonized rice husk *karbonizirane rižine ljuskice*	n/a	polydimethyl-siloxane *polidimetil-siloksan*	n/a	400-500 °C / 75 min	n/a	n/a	n/a	n/a
Chen *et al.* (2020)	carbonized cellulose nanofibers *karbonizirana celulozna nanovlakna*	3 wt%, 5 wt% and 7 wt%	polydimethyl-siloxane *polidimetil-siloksan*	n/a	800 °C / 2 h	5.16	< 16.89	loaded / *opterećen*: 65 unloaded / *neopterećen*: 52	30,000
Chang *et al.* (2019)	carbonized cotton fabric *karbonizirana pamučna tkanina*	n/a	thermoplastic polyurethane *termoplastični poliuretan*	n/a	800-900 °C / 1 h	80.59	/	/	4,000
Chen *et al.* (2018)	carbonized crepe paper *karbonizirani krep-papir*	n/a	polydimethyl-siloxane *polidimetil-siloksan*	(10×10×1.7 mm^3)	up to-900 °C / 7 h	5.67 [0-0.42 kPa] 2.52 [0.42-2.53 kPa]	< 20	loaded / *opterećen*: 30 unloaded / *neopterećen*: 25	3,000

use in monitoring the users' habits and health. Sensors implemented in seating furniture are one of the solutions for monitoring sitting habits and indirectly mitigating the negative consequences of poor sitting.

This paper analyzes a part of the research that includes the production and application of pressure sensors from carbonized biomaterials. Although the research focused on sensors that can be built into seating furniture, so far, the results have not provided the desired answers. However, the results offer an overview of technologies that, with further research, likely have the potential to be incorporated into seating furniture. Precisely the sensors analyzed in this paper, considering their excellent properties, low manufacturing cost and organic origin of the material, have great potential in the wider application of sensors for monitoring sitting habits.

Analyzed sensors showed excellent sensitivity and as such could be used to monitor sitting habits. Considering their small thickness and simple construction, the sensors could be implemented in chair seats, for example in the layer between the seat foam and the seat base. In the same way, they could be implemented in the backrest or armrests, thus covering all the key parts related to habits, i.e. the quality of sitting. In this way, the chair could remain aesthetically and functionally unchanged, while at the same time being enriched with sensors that monitor the sitting position of the user.

Despite the exceptional sensitivity, the problem of implementing these sensors in seating furniture is their repeatability (durability). Given that numerous changes in pressure load occur during sitting, almost all analyzed sensors would lose their function very quickly. As a possible pilot solution, a sensor based on carbonized lignin and PDMS, characterized by repeatability of 100,000 cycles, could be used. To solve the problem of repeatability, at the expense of sensitivity, the durability of the sensor could be increased. According to previous research, this could be done by adding a larger percentage of the resin matrix to improve the mechanical properties of the sensor. However, this would likely impact the sensitivity and conductivity of the sensor. Nonetheless, sensors produced in this way would have better durability, and considering that furniture involves much higher forces than robotic skin or devices for monitoring physiological signals, the reduced sensitivity should still be sufficient to collect information related to monitoring sitting habits.

During the research of the most suitable bio-sensors for use in seating furniture, unfortunately, not a single paper was directly related to such an application of bio-sensors for any kind of furniture. Therefore, new research is needed, which will focus on the implementation of bio-sensors in furniture for sitting, as well as on the search for possible solutions that would be further improved and adapted to the application in furniture.

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