Bibliometric Analysis on Biosensors and their Applications in Agriculture

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Abstract: Biosensors are systematic devices that detect signals from biochemical substances and convert them into quantitative data. They aid in preventing and diagnosing potential diseases and pathogens. The ease of use and accessibility of these devices has paved the way for many technological advancements, especially in the agricultural sector. In this study, the impact of piezoelectric, electrochemical, optical, and molecular biosensors in agricultural settings were analyzed using a bibliometric analysis software called VOSviewer. Various parameters and data sets such as biosensor trends, keyword relationships, and biosensor citation prevalence were used. The created maps showed that in the variable for co-authorship, Chinese authors were among the most prominent; while in the variable for co-occurrence: biosensor, agriculture, and biosensing techniques were among the top three words used; and in citation analysis for countries: China, United States, India, and Italy were the top countries with the most research and contribution in the field of biosensors. The results in this research will aid future studies and workings on biosensors by highlighting plausible trends and prospects in the field of research.

Key Words: plant biosensor; agriculture; farming; advancements; bibliometric

1. INTRODUCTION

Biosensors are scientific devices that produce optical, thermal, or electrical signals in proportion to their analyte by using biochemical reactions (Kumar & Upadhyay, 2018; Oluwaseun et al., 2018). Most biosensors consist of the following parts: analyte, bioreceptor, transducer, electronics, and display (Bhalla et al., 2016). There are distinct qualities that biosensors need to attain optimum performance levels, namely: selectivity, reproducibility, stability, sensitivity, and linearity. In farming, they are used in preventing and detecting diseases, crop pests, and pathogens (Oluwaseun et al., 2018; Bagde & Borkar, 2013). Moreover, this technology can aid in maximizing the quality of crops or products that farmers grow, as stated by Bhalla et al. (2016). For instance, biosensors could monitor the quality of the soil, water, and air of the surrounding areas by noting the pollutants present.

Biosensors are classifiable according to the method by which signal is transduced from the specimen to the device, e.g., optical, electrochemical, thermometric, piezoelectric, and magnetic (Damborský et al., 2016). Recently, there has been another biosensor aside from what was mentioned that is considered as emerging, known as molecular biosensors. The research addresses four classifications of biosensors: piezoelectric, electrochemical, optical, and molecular biosensors. Piezoelectric biosensors, or acoustic biosensors, utilize mechanical waves to detect and obtain biochemical and biophysical information about the compound of interest. It detects changes in any physical property, e.g., mass elasticity and conductivity. Electrochemical biosensors can distinguish hybridized DNA, neuron tissue, bacteria, and enzyme reactions as biochemical events (Li et al., 2017), and convert these into electrical signals (Cho et al., 2020). Optical biosensors measure the responses of target analytes to illumination or light emission by utilizing various techniques. These techniques include light absorbance, reflectance, fluorescence, and more. Lastly, molecular biosensors utilize certain biochemical reactions moderated by biological materials, e.g., enzymes and cells, to detect chemical compounds through electrical, optical, or thermal signals (Campuzano, 2017). The research focuses on one specific type of molecular biosensor, the loop-mediated isothermal amplification (LAMP) biosensor.

Technological advancements in these devices have brought significant changes to the agricultural sector by playing a crucial role in protecting plant crops for quite some time. However, the gap in technological know-how and expensive developmental processes have hindered some countries from incorporating biosensors into the agricultural sector. Most of said countries are third-world countries where agriculture is still developing, and traditional farming methods are employed to maximize crop growth. If biosensor technology continues to advance, cheaper alternatives to current technology will emerge, giving the marginalized agricultural sector the technological opportunity to improve crop production. With that being said, the need for cheaper alternatives for biosensor utilization and production requires further research and development.

This research is focused on biosensors often used in plant agriculture. The study aims to examine the importance of biosensors in plant crops, and to determine the trends of biosensor research according to the year they were published. Moreover, the roles, applications, and uses of biosensors in farming agriculture were explored and discussed. Hence, the results of this study serve as a basis for future research by means of highlighting the trends and important concepts of different biosensors used in plant agriculture. Recent studies about plant biosensors and their uses were also compiled and reviewed.

2. METHODOLOGY

2.1. Data Source

Scopus (https://www.scopus.com), is a bibliographic database containing a large variety of subject areas (E.g., Biochemistry, Arts and Humanities, Chemical Engineering, etc.). This navigation tool is generated by Elsevier, a Netherlands-based company, known for containing numerous published works from different publications and journals. This database was used as the primary bibliographic source for data and collecting articles relating to advancements or studies of biosensors for plant agriculture. The collected data, stored within a comma-separated value (CSV) file, was then processed through VOSviewer (ver. 1.6.15). CSV files collate data of different journal's various parameters from databases. These parameters include but are not limited to document title, authors, and DOI.

2.2. Data Collection

In the data mining and mapping, the search queries "agriculture AND biosensor" were used, and this premise only searches all journals with both words in the title or the abstract. The query string used was "TITLE-ABS-KEY (biosensor AND agriculture) AND DOCTYPE (ar) AND PUBYEAR > 2004", which translates to: articles with keywords "biosensor" and "agriculture" in the document title, abstract, or keyword, ranging from 2005 to present. The result yielded 153 documents in total. The "ar" in the query string denotes "article." Since the scope of this research is for the application of biosensors only in plants, the proponents checked each document to ensure the documents were suited only to plant agriculture. After thorough reviews, fifty-one (51) of the documents were removed, most of which were related to human medicine and animal livestock.

2.3. Bibliometric Maps

VOSviewer is a software capable of creating visual aid maps that connect data through relations between keywords, authors, publications, research, etc. (Van Eck & Waltman, 2011). This software is utilized by a wide user base for establishing correlations amongst data from a pool of journals and articles, which may take form in a distance-based, graph-based, or timeline-based mapping system (Van Eck & Waltman, 2014). The map produced by VOSviewer will be based on the various parameters as mentioned previously, and may also be interpreted in several ways, i.e., size, color, distance, and connections of the data. Furthermore, these interpretations dictate the several aspects of the data (Van Eck & Waltman, 2020). For instance, size difference may determine the number of times a specific term appeared in the data, distance may determine degree relation, and connections may determine presence of a relation between terms.

The data sets were then organized using the bibliographic-data-based using VOSviewer mapping, which is based on the bibliographic data extracted from Scopus. Three types of analysis were employed: co-authorship, co-occurrence, and citation (country).

2.3.1. Analysis of Co-authorship

In the analysis of co-authorship, VOSviewer found 446 authors. However, counting manually, a total of 461 authors, most of which had the same surname and initial (e.g., Liu, X.) were found. Consequently, the map was created based on the initial finding of 446 authors, as that was the number recognized by VOSviewer.

2.3.2. Analysis of Co-occurrence

In the analysis of co-occurrence, "all keywords" were considered, i.e., both "author" and Scopus "index" keywords. Full counting method was employed, and a thesaurus was used to eliminate terms with identical definitions, plural forms, and irrelevance to the study, thus, excluding words such as "organo-phosphorus compound/organophosphorus compound," "soils/soil," and "article."

The minimum number of occurrences that were used was five (5), preventing irrelevant words from being added to the map. The parameters resulted in a total of 57 keywords, after eliminating words with less than five occurrences and words excluded and combined by the thesaurus.

2.3.3. Analysis of Citation

In this analysis of citations, the measured quantity is the countries involved in publishing the articles. The threshold for minimum number of publications was set to one (1), ensuring inclusivity of the available countries. The total number of countries resulting from this set parameter is 44.

3. RESULTS AND DISCUSSION

The researchers conducted bibliometric mapping based on three types of analysis: co-authorship, co-occurrence, and citation, and accordingly, used authors, all keywords, and countries, respectively. The maps produced will be described and analyzed through their physical attributes and characteristics such as size, clustering, color, and line thickness. The data extracted from Scopus were divided into five (5) distinct categories. The central search premise was "biosensor AND agriculture."

3.1. Publication Growth Over the Past Years

From 2005-2020, there has been a significant growth in yearly publications about biosensors used in agriculture (Figure 1). In the years 2005-2010, the average number of publications was 2.67 articles a year. In 2016-2020, the average was 10.8, which indicated a 404.5% increase in mean publications per year. Kundu et al. (2019) attributed advancements in other fields of sciences such as material science and nanoengineering to the increased attention and production of journal articles in the field of biosensors.

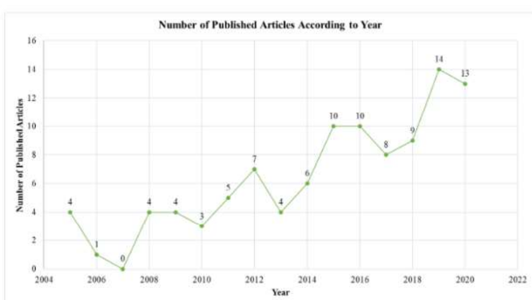

Fig. 1. Number of publications in the recent years from 2005-2020.

3.2. Co-authorship

For the search "biosensors" and "agriculture," consisting of 102 documents, VOSviewer only identified 446 total authors. However, 461 total individuals were found responsible for authoring the 102 articles. Some authors such as Liu, Y., Liu, X., and Wang, Y. have the biggest nodes for the (Figure 2), and although this signifies more written works, it was found that these authors are different individuals. However, other nodes showing the same size, such as He, H. and Wen, Y., signify an equal number of authored works.

The authors clustered are termed co-authors. A green cluster consisting of He, H., Wen, Y., etc. represents one article, while the pink cluster consisting of Pu, Y., Liang, G., etc. represents co-authors of another article. Bigger nodes, such as Liu, Y., Liu, X., and Wang, Y., are positioned to be proximally close to the authors they have worked with individually. According to the numerical data extracted from VOSviewer, Liu, Y. authored three articles; concurrently, three different authors named Liu, Y. were found to author the three different articles. The observations in color and line thickness show no significant role in identifying relations between the authors.

As mentioned, there were 446 total identified authors by VOSviewer. However, Figure 2 only represents a portion of the 446 authors since only the cluster with the most connection can be displayed. Other authors with high link strengths which are not connected to this big cluster are not shown in the map provided.

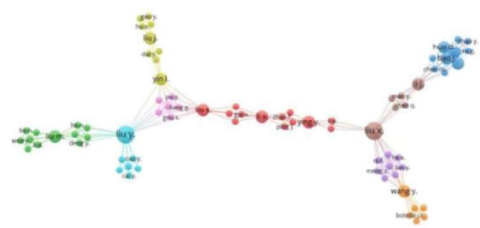

Fig. 2. Co-authorship mapping using VOSviewer.

3.3. Co-occurrence Variable

The top three most occurring keywords are biosensor, agriculture, and biosensing techniques (Figure 3). "Biosensor" and "agriculture", being the search premises, were the highest with 69 and 40 occurrences, respectively. Node size is directly proportional to the frequency of the keyword, Figure 3 has clusters which are grouped into distinct colors: red, yellow, green, purple, and blue. The colors represent a common theme or relation among the words, as observed in a study performed by Briones-Bitar et al. (2020).

The observed theme among the clusters are as follows: agriculture and biosensing (keywords: "agriculture," "biosensor;" red cluster), chemistry (keywords: "metabolism," "limit of detection;" blue cluster), pesticides and words associated to chemicals (keywords: "acetylcholinesterase," "organophosphate pesticide;" green cluster), chemical processes (keywords: "colorimetry," "chemical detection;" yellow cluster), and metals and other materials (keywords: "graphene," "gold;" purple cluster).

The link strength of each keyword is attributed to the line thickness and size of its node. According to Md Khudzari et al. (2018), line thickness in the maps represent a higher link strength, and as observed, keywords such as biosensor and agriculture have thick lines running across the map and a link strength of 401 and 273, respectively.

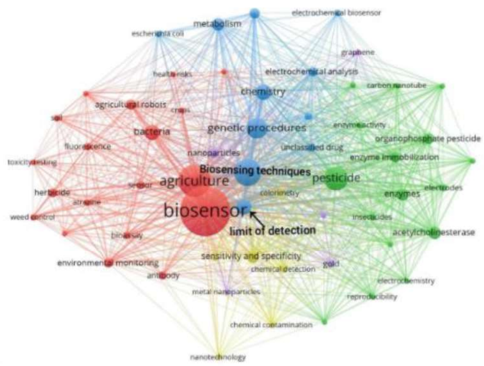

Fig. 3. Co-occurrence mapping from VOSviewer.

3.4. Country Variable

Countries mostly involved in the development and studying of biosensors in agriculture are highly developed countries. The countries with the most publications are China (24), United States (14), India (13), and Italy (13). The productivity of these countries is most likely a result of their high competitiveness and high funding allocation. China and India are two of the most populated countries in the world; hence, a large amount of agricultural production is required to support their country, which may explain the amount of effort they put into the pursuit of biosensor research.

The cluster or proximity of the nodes for Figure 4 indicate how closely countries work together in their research or how much the authors of each country cite each other's work. India is located at the center of the map, which indicates extensive collaborations with its corresponding countries in the map such as China, Poland, and Italy.

Among the top four, India and China have the highest link strengths (8). These two countries have not only published several articles for biosensors, but also have collaborated with other countries. The thickness of the lines that connect them with other nodes are significantly thicker than other countries, which possibly reveal the great strides these two countries have taken to enhance the use of biosensors in agriculture.

Fig. 4. Citation mapping with VOSviewer.

4. CONCLUSIONS

Overall, the results from the bibliometric analysis through VOSviewer show that in the link for co-authorship, most authors were clustered to be Chinese. For co-occurrence, on the other hand, the top words were biosensors, agriculture, and biosensing techniques. The citations for the country variable section indicate the top three biosensing research to be China, India, and Italy, with the first two countries being in the same field of biosensor research. In the future, the possible research in biosensor use and study will be heavily focused on by developing and agricultural-focused countries which is a highly relevant explanation as to why China and other similar countries have a high biosensor research footprint. As research on biosensors progresses further, it is important to be able to determine the trends in keywords and uses in citations by different authors and countries in order to foresee the possible direction this research is heading for.

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Studies on the Morphological and Mechanical Properties of Oil Palm Empty Fruit Bunch-derived Nanocellulose for Supercapacitor Applications

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Abstract: Electricity is an essential resource and aspect of our daily lives. To cope with its high demands, supercapacitors and more efficient batteries have been introduced to the market; the separator is an integral part in the performance of supercapacitors. This study determined the morphology, chemical composition, and mechanical properties of oil palm empty fruit bunch nanocellulose as a separator for supercapacitors and compared its performance with other agricultural materials (e.g. eggshell membrane, cotton textile, and tree leaves) and an membrane electrode assembly. The OPEFB nanocellulose has the morphology and mechanical properties that make it a possible supercapacitor separator material. The porous agglomerate of microfibers and surface nanostructures provide higher effective surface area and may aid in the diffusion of ions. Measured Young's modulus of 6.00 MPa/%, yield strength of 3.20MPa, and tensile strength of 5.30MPa are comparable to separators used in commercial supercapacitors and the reported eggshell membrane separator. This study provides sustainable and "green" alternatives for current commercial supercapacitor separators.

Key Words: nanocellulose, separator, supercapacitor, mechanical strength

1. INTRODUCTION

A supercapacitor is an electrochemical energy storing device used to power technology in various fields ranging from the military to the automotive industry. It has four major components: electrodes, current collectors, electrolytes, and a separator (Nor et al., 2014). The positive and negative electrodes are divided by a non-conductive material called a separator and a small distance to allow for greater storage of electrical energy in a smaller area of space (Dume, 2017).

Separators act as a barrier to prevent short-circuiting by the direct contact of the opposite polarities and to allow the easy flow of electrolytes (He et al., 2017). Present supercapacitor separators use polyolefins for electrochemical stability; however, their low porosity does not meet the high energy needs of the supercapacitor (Du et al., 2017), and the mechanical deformability (Azais et al., 2016) can lead to circuit shortage. Polyolefins are also nonrenewable, unsustainable for mass production, and hold around 20 to 30% of space in landfills (Longo et al., 2011). An example of a polymer-based separator is a Membrane Electrode Assembly (MEA) commonly used in fuel cells (Fuel Cell Store, n.d.). One of the most common membranes in the commercial market is Nafion™, a perfluorosulfonic acid polymer membrane (Kundu et al., 2005).

Cellulose, and its nanoscale forms, is a natural polymer with innovative applications in materials science (Klemm et al., 2018). Moreover, nanocellulose (NC) has emerged as a promising material for separators. Aside from being sustainable, NC separators have electrochemical and mechanical stability which are essential in a supercapacitor (Guo et al., 2020).

In this study, NC from oil palm empty fruit bunch (OPEFB) was characterized as a separator material for supercapacitor applications. OPEFB is a major waste product of the palm oil industry. As of 2013, the Philippines produces an average of 120,000 tons of oil palm (Philippine Coconut Authority, n.d.). With the rise of agricultural waste, waste management methods have been proposed which include waste recycling and deriving energy from waste (Abdullah & Sulaim, 2013). The OPEFB can be collected during the recycling process of agricultural wastes, and then made into a separator. It has been successfully made as a bioplastic (Iriani et al., 2019) and used as an electrode (Nor et al., 2014). Furthermore, NC has proved to have excellent electrochemical and mechanical properties; its rich carbon content and high porosity ensure outstanding electrochemical performance (Guo et al., 2020). Separators made from agricultural products can be locally produced, making technology more accessible to developing countries. This study will benefit the fields of materials science and electrochemistry while also encouraging sustainable energy initiatives from the government.

In this study, the morphological, chemical, and mechanical properties of OPEFB NC as a separator were investigated. Specifically, the authors:

characterized the OPEFB nanocellulose in terms of its surface morphology and chemical composition by scanning electron microscopy and energy dispersive spectroscopy and mechanical properties, i.e. mechanical strength, and stiffness, by a comprehensive materials testing system;

measured the stiffness of the separator material through Young's modulus, its yield strength, and tensile strength; and

compared the morphological and mechanical properties of OPEFB nanocellulose with that of MEA 144A and other separator materials made from agricultural wastes reported from previous studies.

2. Cellulose-based Materials for Supercapacitors

2.1 Oil Palm Empty Fruit Bunch (OPEFB)

OPEFB is a byproduct of palm oil production (Han and Kim, 2018) composed of cellulose, hemicellulose, and lignin (Rosli et al., 2017). It contains around 40-44% of cellulose (Foo et al., 2020), so it may be deemed a potential source of NC (Septevani et al., 2020). Aside from its content being notable, it has high availability due to its abundance in Southeast Asian countries. OPEFB also accounts for ⅓ of oil palm biomass (Geng, 2013). Thus, it is a reliable and sustainable source of NC for supercapacitor applications.

In the study of Teow et al. (2020), the OPEFB diameter decreased from 228.88 ± 6.63 μm to 13.63 ± 3.10 μm after cellulose extraction as seen in the scanning electron microscope (SEM) analysis displayed in Figure 1. It can be inferred that it is possible to use cellulose as a separator as its size can be reduced to fit the supercapacitor.

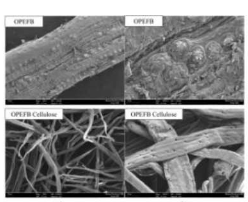

Figure 1. *SEM micrographs of the OPEFB and cellulose extracted from the OPEFB under different magnification: (a) 250 × (scale bar 20 μm) and (b) 1.00 k (scale bar 10 μm) (Teow et al., 2020)*

Previous works have applied OPEFB in supercapacitor electrodes (Ishak et al, 2015; Dolah et al, 2014; Farma et al., 2013); however, no study has used it as a separator.

2.2 Mechanical Properties of Previous Studies

Mechanical properties play a big role in characterizing the quality of cellulose material. Through these, the performance of a separator may be expected. Given the position of a separator, it needs to have minimal resistance from the movement of electrolyte ions (Yu et al., 2012). Properties that could predict the performance of the separator include surface morphology, mechanical strength, and stiffness. The surface morphology of a material can be utilized to characterize the porosity and material structure (Adeleke et al., 2019). The mechanical strength and stiffness of a separator also play a crucial part in characterizing the possible life span of the supercapacitor and other energy storage devices. The study conducted by Mandake and Karandikar (2016) showed that thicker separators would correspond to lower porosity. Considering that high porosity is needed in a separator, it should be thin enough for high porosity while maintaining a good mechanical strength and stiffness. In the studies of Gao (2015) on cotton textile as a separator, Yu et al. (2012) on eggshell membrane as a separator, and Jin et al. (2019) on tree leaves as a separator, the results showed excellent mechanical strength and properties alongside high porosity and superb electrochemical properties.

A source that has been used as a separator material is eggshell membrane (ESM) (Yu et al., 2012). It has high mechanical strength, with reported maximum stress and maximum strain values of $\sigma max = 6.59 \pm 0.48$ MPa and $\varepsilon max = 6.98 \pm 0.31\%$, respectively. Figure 2 displays the surface morphology of the eggshell membrane showing shell membrane fibers of thickness 0.5 to 1 μm, and pore sizes of 1 to 3 μm.

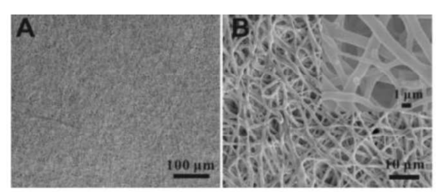

Figure 2. *SEM photographs of ESM at low (A) and high (B) magnifications (Yu et al., 2012)*

The cotton textile was also reported to show ideal surface morphology as a separator material. The nanostructure and nanowires found on the surface of the material (Figure 3) were found to have minimum dimensions of 5μm and 20μm, respectively (Gao, 2015).

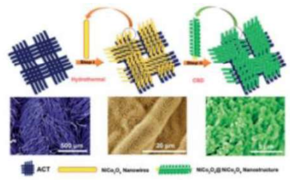

Figure 3. *Illustration of the nanostructures of NiCo2O4@NiCo2O4 covering activated carbon textiles (ACTs) (Gao, 2015)*

The application of four different tree leaves to create a separator for a graphene-based supercapacitor was investigated by Jin et al. (2019). These four tree leaves are cinnamomum camphora (CC), magnolia grandiflora (MG), platanus orientalis (PO) and osmanthus fragrans (OF). The separator made from activated CC showed most promising results. Figure 4 shows the surface morphology of the 4 leaves at a bar of 10 μm. The mechanical properties of the separator materials based on agricultural sources discussed are summarized in Table 1.

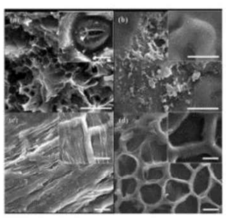

Figure 4. *SEM images of the 4 different activated tree leaves: (a) CC; (b) MG; (c) PO; (d) OF. All bars are at 10 μm. (Jin et al., 2019)*

Table 1. *Comparative Summary of Mechanical Properties of Separators Based on Agricultural Sources*

Paper Title and Author	Agricultural Source	Mechanical Properties		
		Surface Morphology	Mechanical Strength	Stiffness
Using eggshell membrane as a separator in supercapacitor (Yu et al., 2012)	Eggshell membrane	0.5 to 1 μm (shell membrane fibers) and 1–3 μm (macropores)	σ_{max} = 6.59 ± 0.48 MPa (maximum stress) and ε_{max} = 6.98 ± 0.31% (maximum strain)	xxx
Cotton textile enabled, all-solid-state flexible supercapacitors (Gao, 2015)	Cotton Textile	5 μm (nanostructure) and 20 μm (nanowires)	xxx	xxx
Tree leaves-derived three-dimensional porous networks as separators for graphene-based supercapacitors (Jin et al., 2019)	Tree Leaves	10 μm	xxx	xxx

2. METHODOLOGY

The separator material used in this study is an oil palm empty fruit bunch nanocellulose (OPEFB NC) film. The OPEFB NC material was characterized to determine its morphological and mechanical properties, as well as chemical composition. A comparative study was done with other agricultural-product based NC separator materials from previous studies and the OPEFB NC investigated in this work on the basis of mechanical strength and surface morphology.

2.1. Research Design

The quantitative characterization techniques used in studying the properties of OPEFB NC are scanning electron microscopy, energy dispersive spectroscopy, and stress-strain test. The surface morphology of the OPEFB NC was measured using a JEOL JSM 5310 scanning electron microscope (SEM). Elemental analysis was done using the EDAX energy dispersive spectroscopy (EDS) system attachment of the JEOL JSM 5310 SEM to determine the elemental composition of the sample (Intertek, n.d.). Furthermore, a PASCO Comprehensive Materials Testing System ME-8244, an equipment used for tensile testing (PASCO, n.d.), was utilized to obtain the stress vs. strain and force vs. position graphs for the OPEFB NC sample. From the stress-strain plot, the mechanical properties, specifically the Young's modulus, yield strength, and tensile strength of the sample were determined. The measured morphology and mechanical properties of the OPEFB NC separator material were then compared with those of eggshell membrane, cotton textile, and tree leaves.

2.2. Data Analysis

For most metals and plastics polymers, stress σ (in Pa) and strain ε are directly proportional to each other, i.e. $\sigma = E\varepsilon$, wherein E is Young's modulus (in Pa) or the modulus of elasticity. In this study, the measure of stiffness of the sample, i.e. Young's modulus, was determined from the slope of the linear portion of the stress-strain curve. As the stress on the sample was increased during testing, the sample experiences a gradual elastic-plastic transition. The yield strength (in Pa) was determined at the point on the stress-strain curve when the curve starts to depart from linearity; this is the amount of stress that the sample can take without undergoing plastic deformation. After passing the yield point, the stress needed to continue the plastic deformation of the sample increases and then reaches a maximum point. The tensile strength (in Pa) is simply the stress at the maximum point of the stress-strain curve. This is the maximum stress the sample can sustain when in tension.

3. RESULTS AND DISCUSSION

The SEM images of the OPEFB NC in Figure 5 show the surface morphology at x10000, x1000, and x500 magnification, respectively. The microfibers of cellulose (~2 to 6 μm) are a disordered agglomeration interspersed with nanoparticles, which are possibly silica on fiber surface, consistent with the report of Mohammad et al. on thermally pre-treated OPEFB used for biofuel production (2020). The presence of silica in supercapacitor electrode or separator materials was shown to exhibit excellent stability and flexibility (Pérez-Madrigal et al., 2016). The size of the microfibers in the OPEFB are comparable to those found in eggshell membranes and cotton textile. The nanoparticles and interwoven microfibers on the surface of the OPEFB sample indicate larger effective surface area, which may aid in better diffusion of ions and in turn good electrochemical performance. The OPEFB surface morphology is smoother compared to that of the eggshell membrane fibers, cotton textile, and tree leaves. This is ideal for a supercapacitor separator material as it allows good contact between the electrodes; however, the OPEFB sample's lower porosity as compared to the other three materials may reduce the ion mobility.

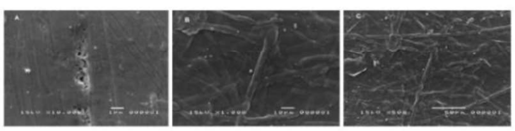

Figure 5. *SEM images of the OPEFB at (A) x10000, (B) x1000, and (C) x500 magnifications, respectively*

The results of the elemental analysis of the OPEFB sample obtained from EDS are shown in Figure 6. The EDS spectra shows that the sample consisted of C (41.26 wt%), O (51.59 wt%), Al (0.58 wt%), Si (0.56 wt%), S (5.44 wt%) and Cu (0.57 wt%).

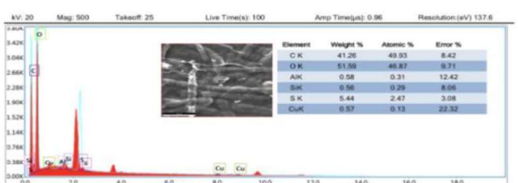

Figure 6. *EDS elemental analysis of OPEFB sample*

The mechanical properties of the OPEFB sample were determined from the plot of the stress-strain data as depicted in Figure 7. On the stress-strain curve, the linear portion of the elastic region is until the applied stress rose to 3.20MPa. Calculating the slope of this linear portion resulted in a Young's modulus of 6.00MPa. At a stress level of 3.20 MPa (yield strength), the curve starts to depart from linearity. This is the point when yielding occurs and plastic deformation of the sample begins. As further stress was applied to the sample, it then fractured when the applied stress reached 5.30 MPa (tensile strength).

Table 2. *Comparison of Mechanical Properties of OPEFB NC, eggshell membrane, and MEA 144A*

Paper Title and Author	Material	Young's Modulus (MPa/%)	Yield Strength (MPa)	Tensile Strength (MPa)	Maximum Strain (%)
Authors' Paper	OPEFB NC	6.00	3.20	5.30	3.45
Using eggshell membrane as a separator in supercapacitor (Yu et al., 2012)	Eggshell Membrane	xxx	xxx	6.59	6.98
Mechanical Properties of Nafion™ electrolyte membranes under hydrated conditions (Kundu et al., 2005)	MEA 144A	3.23	2.19	xxx	xxx

The tensile strength of the OPEFB NC is slightly lower than that of the eggshell membrane separator material (Table 2). However, compared to the MEA 144A separator used in commercial supercapacitors, the Young's modulus of OPEFB NC is almost twice. This implies that OPEFB NC separator has sufficient strength to prevent contact between electrodes and will be able to maintain integrity during manufacturing and transport. This structural integrity in OPEFB NC is also necessary as separators swell and deform during the charge-discharge process.

4. CONCLUSIONS

The OPEFB NC separator has the morphology and mechanical properties that make it a possible supercapacitor separator material. The porous agglomerate of microfibers and surface nanostructures provide higher effective surface area and may aid in the diffusion of ions. Measured Young's modulus of 6.00 MPa/%, yield strength of 3.20MPa, and tensile strength of 5.30MPa are comparable to separators used in commercial supercapacitors and reported separator material from eggshell membrane. For future studies, the electrochemical properties should also be investigated to further assess its suitability as a supercapacitor separator.

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