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REVIEW **Open Access**

Dielectric materials development using bio-waste: a review

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Abstract

The increasing global demand for food due to population expansion has led to the intensification of the agricultural sector. However, this escalation in agricultural production has brought together undesirable consequences as more waste is produced, leading to growing environmental concerns as proper disposal of these wastes is necessary. Valorization of these bio-wastes into dielectric materials offers a promising solution to conventional, non-renewable, yet costly materials. Comprehensive documentation on the development of these wastes into dielectric materials is then necessary to understand their dielectric properties and how these materials behave with the treatments during the fabrication process. This review focuses on the state-of-the-art development of dielectric materials derived from bio-wastes and agricultural waste, which are beneficial for waste management and materials engineering applications. The elemental composition of the waste materials is also discussed in this review to understand its relationship with the dielectric constant. Moreover, the fabrication process for several waste materials into dielectric materials has been provided and compared. This review provides comprehensive information on green materials in the materials engineering industries and can assist in novel studies. It is foreseen that bio-wastes and agricultural wastes can be renewable, sustainable, and low-cost resources for deriving dielectric materials in light of their ease of accessibility.

Keywords: Dielectric materials, Dielectric properties, Bio-waste, Agricultural waste

Introduction

The dielectric material is a poor conductor of electric current, also called an electrical insulator, that can be polarized by an electric field [1]. Electric charges stop flowing through the material each time the dielectric is placed in the electric field. However, a slight change from their average equilibrium position can cause dielectric polarization [2]. The dielectric is used to define the ability of materials to store energy.

Teflon, alumina, and mica are examples of conventionally used dielectric materials that are in high demand in the market. Teflon, also known as polytetrafluoroethylene, has excellent properties for thermal and electrical insulation due to its capability to withstand temperature. The robust chemical bond between fluoride and carbon in Teflon has resulted in Teflon being good insulation stability and a low friction coefficient, as well as being chemically inert [3]. Teflon is a material commonly used in electrical, electronic and medical applications as dielectric materials [4]. Teflon has been widely used in the electrical and electronic fields to produce semiconductor and insulation materials [5]. Teflon can also be used for ligament replacement or heart patches in medical applications. Teflon is also used in the industrial sector to produce pumps or reaction vessels. Nonetheless, Teflon is expensive and difficult to produce on a large scale. Also, Teflon cannot be cemented and can deform under pressure, other than being incapable of resisting very high temperatures [6].

Alumina is an electrical insulation material commonly used in high-temperature applications due to its ability to demonstrate elevated toughness and refractory character [7, 8]. Alumina exhibits excellent mechanical properties with a high melting point and low density. Moreover, alumina has good thermal shock fracture resistance with chemical and heat stability with outstanding toughness and strength [9, 10]. Alumina has generally been used as a hip implant material for the human body and in dental implants through in-vivo applications as a dielectric material [11]. However, besides being complex and expensive, alumina has moderate tensile and bending resistance, is brittle, and has low electrical and thermal conductivity.

Mica is a generic name for a natural mineral belonging to the potassium alumino-silicate hydrate family [12, 13]. Mica has outstanding stability and fire resistance which can withstand high temperatures of 600–900 °C [12, 13]. Mica is exceptionally stable and practically immune to all solvents, alkalis, and acids [12, 14]. In mechanical application, mica is very versatile; however, its strength remains high and strong [12]. Moreover, mica also exhibits high dielectric strength with low power loss, stable dielectric constant, and high electrical resistance in electrical applications [12, 15]. The use of mica in mechanical devices is demonstrated by the unbreakable safety glasses, fireplaces, and lantern windows [14]. Mica can be used in industrial applications, such as local heating equipment, soldering irons, or thermostats [13]. Mica is also used in electrical and electronic devices such as high-voltage transformers or thin dielectric films in capacitors. Nonetheless, similar to both Teflon and alumina, mica is a high-cost material [15].

Since this conventionally used dielectric material is a non-renewable material that might be depleted in future, a dielectric material made from bio-waste is introduced. The bio-waste or biodegradable waste consists mainly of organic materials, including food, green and paper waste, and even biodegradable plastics. The utilization of bio-waste and agricultural waste in engineering applications could reduce the environmental issues that arise from the improper disposal of both wastes. With the ease of accessibility, these wastes can be potentially used as a replacement for the expensive conventional dielectric material. The continuous use of these wastes is forecasted to fulfill the increasing demand for material due to the exponential growth of the human population. Besides being both financially and environmentally friendly, using renewable sources may reduce the use of non-renewable sources, eventually leading to the preservation of the materials for the next generation. The application of bio-wastes and agricultural waste should be widened in any field owing to their outstanding properties.

Types of dielectric material

The dielectric material can be divided into three types based on the condition of the material, which are solid, liquid, and gases, with solids as the most common. Solid dielectric consists of two groups of inorganic and organic materials. Examples of inorganic materials include ceramics and asbestos, while paper and polymer are organic materials.

Dielectric ceramics are electrical insulators with dielectric constant, dielectric strength, and loss tangent that can be adapted to the application of a specific device or circuit. Ceramics is a long-lasting product with outstanding durability, moisture, and chemical properties, making it suitable for dielectric material [16]. Their thermal–mechanical activity is also one of the characteristics of ceramic material, including expansion coefficient, thermal conductivity, capacity, and the capability of withstanding high temperatures [16, 17]. Ceramic material is used for insulation and buffers in power systems due to its high mechanical strength. Due to their low permittivity, the ceramic material is also used for millimeter and substrate wave communication for integrated microwave networks. The ceramic material can be used for satellite communications and mobile phone base stations at medium or high permittivity [18].

Asbestos is extensively used globally due to its excellent physical properties, such as poor heat conduction, great tensile strength, high flexibility, and low cost. Besides being non-biodegradable and non-flammable, asbestos is resistant to high electrical, temperature, acid, and alkali and can absorb sound [18–20]. Asbestos is commonly used in fire-resistant insulation boards, pipe lagging, friction material for vehicle brakes and clutches, and many other building materials [21]. Asbestos is also applied in electrical components such as cable wrap, molded cement bases, wire insulation, and electrical shielding.

Polymer is one example of an organic solid dielectric that is often used as an insulating material to protect cables and electrical equipment in the power cables industry [22, 23]. The dielectric characteristics of polymers are easy to process and manipulate, cheap, versatile, lightweight, non-toxic, high reliability, and low dissipation factor, which can quickly adapt to new applications [22, 24]. Also, the dielectric polymer exhibits outstanding chemical resistance. With these properties, the polymer can produce an organic solar sail, organic light-emitting diodes, and rechargeable batteries for electrical applications [25].

Another example of organic solid dielectric material is paper. Paper is made from cellulose that is obtained from pine wood. Paper is called a fibrous insulating material due to its fibrous structure [26]. The characteristics of the paper are low dielectric loss, inexpensive, lightweight, as well as sufficient mechanical strength. Also, the paper is easy to obtain due to its wide availability and is easy to wrap around the conductor [26, 27]. Paper can also be used in electronic applications to make telephone cables and capacitors [26].

A liquid dielectric material is used for impregnation and filling functions in various essential electrical appliances [28]. These are due to its properties that serve as a diagnostic medium, refrigerant, and electrical insulator [26, 27]. An example of liquid dielectric is transformer oil, known as excellent mineral oil with excellent electrical insulating properties and is stable at high temperatures [29]. Transformer oil can be used in capacitors, bushing insulators, reactors, and oil circuit breakers [30]. Moreover, transformer oil can also be used to prepare the arc quenching medium, which acts as an insulator between copper-losing windings to reduce the heating and humming noise produced in the transformer [31]. In addition, transformer oil is used in fluorescent light ballasts, oil-filled transformers, high-voltage switches, circuit breakers, and capacitors [29].

Dielectric gas is a dielectric material in a gas state that quickly prevents or extinguishes electrical discharges. Dielectric gas is used in high-voltage applications such as circuit breakers and transformers as electrical insulators. An excellent dielectric gas is a gas that has high dielectric strength, high thermal stability, good heat transfer properties, non-flammability, low boiling point, less toxicity, and low cost [32]. Air and nitrogen are examples of dielectric gaseous [33]. Air is a natural dielectric gas that can be naturally found around the transmission and distribution conductors. Also, the air is deemed an electropositive dielectric gas that insulates plugs, switches, and overhead transmission lines [26]. Nitrogen is another gas that is commonly used in gaseous dielectric processes. Nitrogen is chemically inert; thus, it can avoid oxidation and reduce the degradation of the apparatus used [34]. Also, nitrogen was often applied under pressure in certain capacitors and used in gas-filled high-pressure cables and oil-treated paper insulation [26].

Bio-waste as dielectric materials

The dielectric constant of bio-waste

Both agricultural and bio-waste poses huge potential as alternative and beneficial innovations for various engineering applications [35], with microwave signal absorbers as the most common. Besides microwave absorbers, materials extracted from agricultural waste can also be utilized as a substitution for the conventional printed board (PCB) and antenna application. Biological and agricultural residues are organic compounds made up of organic sources such as rice husks, rice straw, coconut shells, oil palm empty fruit bunch, corn husks, and sugar cane bagasse. There are several advantages of using agricultural waste to produce dielectric materials. Besides being environmentally and economically friendly, agricultural waste is a renewable source of elements and a better way of managing many agricultural wastes for producing various engineering materials. Table 1 presents the chemical elements of selected agricultural wastes and their corresponding dielectric constant value.

Agricultural waste is a non-hazardous natural source of lossy carbon that can be applied as polymer matrix filling for the absorption of electromagnetic interference (EMI) noise [46]. Rice husk is a by-product of paddy (*Oryza sativa*) [47, 48], which owns absorbent [49] and insulating properties that help many industrial applications [50]. Rice husk has been used in biomass fuels to generate power and in concrete mixtures for the construction of buildings [51], as well as microwave absorber fabrication [47, 50]. Rice husk is difficult to dispose of, especially since the rough surface of rice husk is very much resistant to the decaying process. The slow decay of rice husk caused the production of methane gas [52]. The carbon content in the rice husk influences the dielectric constant value, where the increment in the percent weight of rice husk ash significantly affects the dielectric constant value [53]. As tabulated in Table 1, 35.77% of carbon elements contributed to the 2.985 dielectric constant value.

Table 1 The elemental percentage for agricultural waste

Elements	Percentage of elements					
	Rice husk [36]	Rice straw [38]	Oil palm empty fruit bunch [39]	Sugarcane bagasse [41]	Coconut shell [42]	Corn husk [44]
Carbon	35.77	38.24	46.83	17.89	53.88	54.99
Hydrogen	5.06	5.2	6.27	5.7	6.56	–
Nitrogen	0.32	0.87	0.66	0.20	0.97	–
Sulfur	0.02	0.1	0.23	2.3	0.03	–
Oxygen	36.59	36.26	45.99	47.7	38.56	24.79
Silica	22.24	13.0	25	2.67	0.98	0.56
Aluminum	–	–	–	1.47	–	0.88
Phosphorus	–	0.27	–	0.75	–	1.11
Potassium	–	2.0	–	0.04	–	3.11
Calcium	–	–	–	0.58	–	3.28
Iron	–	–	–	0.4	–	0.94
Ash	20.0	18.67	6.69	1.42	0.56	2.93
Dielectric constant	2.985 [37]	3.231 [36]	3.455 [40]	2.791 [36]	3.769 [43]	3.900 [45]

Rice straw is the by-product of rice production during harvesting and the paddy plant's vegetative part [38]. Before the subsequent plowing, it may be left on the field, plowed down as a soil enhancer, or applied as livestock feed. However, only a tiny fraction of straw is taken for livestock feed, whereas the remainder is openly burnt, triggering environmental pollution [54]. Rice straw is distinctive from other cereal straws, which are high in silica and have low lignin content [55]. Rice straw contains lignocellulosic material, consisting of cellulose, hemicellulose, and lignin, that is degradable into cellulose [38]. These lignocellulose materials have been widely used as materials for particleboard manufacturing. Also, rice straw is applied in numerous industrial applications, such as cosmetics, medicines, building materials, biopolymers, insulation boards, and fine chemicals. As displayed in Table 1, rice straw exhibits a dielectric constant value of 3.231, which may be attributed to the high carbon percentage in these waste materials.

Oil palm empty fruit bunch (OPEFB) is typical in Malaysia as Malaysia is a global palm oil exporter. It is approximated that the output of OPEFB contributes to 19.5 million tons per annum. OPEFB is a solid waste product from the oil palm milling process obtained from empty fruit bunches. OPEFB is high in moisture and silica content, with an approximate value of 55% to 65% and 25%, respectively. The carbon content in OPEFB (46.83%) is considerably high, which explains its high dielectric constant value of 3.455, as portrayed in Table 1. The application of OPEFB as a reinforcing material can reduce the associated costs, improve rigidity, enhance thermal stability, and improve the dielectric and mechanical properties of any mixture [40].

Sugarcane bagasse is a significant agricultural waste and a residual generated in sizeable quantities by the sugar industry after the extraction and use of juice for sugar production [56–58]. Sugarcane bagasse is commonly used to manufacture high-quality green products due to its cost-effective production [52]. The mechanical properties of sugarcane bagasse are good in bending and tensile strength, bending modulus, impact, and hardness [59]. Also, sugarcane bagasse can absorb water quickly and is a low-value agro-waste product. Sugarcane bagasse can be used in many industries and applications. For instance, sugarcane bagasse is used in manufacturing microwave absorber fabrication to eliminate or destroy the reflected signals in the anechoic chamber [57]. Sugarcane bagasse can also be used in pulp manufacturing, paper, building boards [60, 61], and thermal and acoustic insulation [62]. Besides, sugarcane bagasse is one of the most effective sources of preparing activated carbon due to the carbon content that naturally exists in sugarcane bagasse [61]. The carbon content of 17.89% in sugarcane bagasse had given rise to the dielectric constant value of 2.791 (Table 1). The carbon content in the bagasse cane can also provide an excellent reflective loss of efficiency. Also, as presented in Table 1, the increase in elements such as iron, phosphorus, potassium, and calcium percentage in sugarcane bagasse led to an increase in dielectric constant value.

Coconut shell is one of the essential natural fillers generated in Malaysia. Coconut shell has good durability characteristics, high strength, and modulus properties, besides being economically and environmentally friendly [63–65]. Besides, coconut shells contain high cellulose and lignin content [66, 67]. The characteristic of coconut shells made them suitable for making activated carbon in a microwave material [66, 68] and in the production of concrete [69]. Coconuts shells used in industry or stores and from households are often discarded after use, which may create severe environmental pollution [65]. Also, the burning of coconut shells can cause air pollution. The carbon content in the coconut shell had shown a remarkable value, with 53.88%, which increased the 3.769 dielectric constant value.

Corn husk is one of the agricultural wastes being produced in a large amount, and the utilization is none other than for livestock feed in a small amount. Corn husk can be converted into silica. Due to its high dielectric strength and mechanical resistance, the amorphous silica extracted from corn husk has been used widely in various industries, including glass, porcelain, and resin production [70]. Corn husk is also used in the production of paper and biodegradable film. The carbon content in a corn husk is higher compared to other waste materials (Table 1), which has better absorption performance [45]. Also, 54.99% of carbon elements in the corn husk contributed to the 3.900 dielectric constant value.

Effect of chemical elements toward dielectric properties

Carbon can be found abundantly in most bio-waste and agricultural wastes. The surface area and the pore structure are the two key factors associated with carbon material. Carbon is suitable for producing thermal energy from microwave energy. Thermal energy is produced from electrical energy when the microwave energy passes through the absorber, generating the electric field occurrence [71]. According to Fendi and Maddu [72], extracted carbon from biomass can potentially be a dielectric material. As displayed in Fig. 1, carbon, nitrogen, and potassium were proportionally related to the dielectric constant value. The capacitance value was measured to determine the dielectric constant value. The dielectric constant value exhibited by the synthesized carbon indicated the ability of carbon in energy storing capacity.

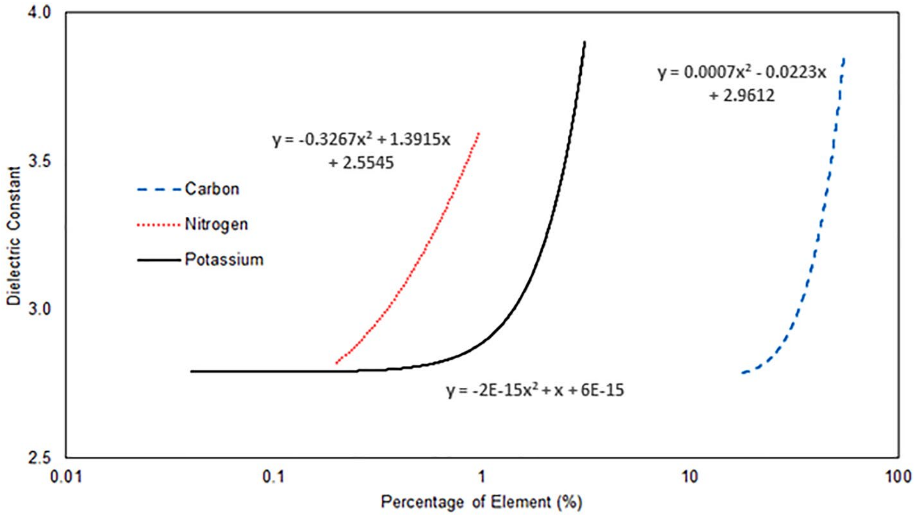

Fig. 1 The percentage of carbon, nitrogen, and potassium on dielectric constant

Guerino et al. [73] stated that the dielectric value increased with the nitrogen content in the diamond-like carbon films, which is comparable with the dielectric constant value. Also, as determined by Arjmand and Sundaraj [74], the dielectric permittivity was increased significantly in nitrogen-doped carbon nanotubes compared to the non-doped ones. The increase in dielectric properties with nitrogen doping might be attributed to the function of nitrogen atoms and crystalline defects that operated as polarizing centers, which facilitate the large absolute permittivity [75]. The finding suggests that nitrogen doping could be introduced as a regulatory factor in controlling the dielectric traits of composite materials. Güler et al. [76] also observed a similar finding in determining the effect of nitrogen and boron doping rate on both electrical and dielectric properties of zinc oxide. The high dielectric constant was obtained in the zinc oxide sample doped with nitrogen. Also, nitrogen doping caused an increase in the zinc oxide capacitance value, whereas doping with boron decreased the capacitance value of zinc oxide.

The addition of excess potassium in the composite of sodium–potassium niobate ceramics resulted in the maximized dielectric permittivity and minimized dielectric loss [77], which might also explain the increment of the dielectric constant value with increasing potassium elements in the waste materials. According to Dhari et al. [78], the composite doped with potassium has a larger dielectric constant than the non-doped composite. Besides, the increase in potassium doping concentration could also increase the dielectric properties due to the increase in the sintering ability of materials achieved at such doping concentration [79]. The dielectric properties of soil samples supplemented with ammonium sulfate and potassium nitrate were studied by Syeda et al. [80]. The finding suggests that the dielectric constant of soil increases gradually with the increase in the ammonium sulfate and potassium nitrate concentration. However, it is interesting to note that ammonium sulfate provides a better increment of dielectric constant value than potassium nitrate, which might be due to the slow decay of potassium nitrate compared to ammonium sulfate. These, therefore, explain the sharp increment of dielectric constant value exhibited by nitrogen as opposed to potassium presented in Fig. 1.

From Fig. 1, the correlation between the percentage of elements (nitrogen, carbon, and potassium) and the corresponding dielectric constant (y) can be expressed as follow.

$$y = -0.3267\mathrm{N}^2 + 1.3915(\mathrm{N}) + 2.5545 \tag{1}$$

$$y = 0.0007\mathrm{C}^2 - 0.0223(\mathrm{C}) + 2.9612 \tag{2}$$

$$y = -2E^{-15}\mathrm{K}^2 + (\mathrm{K}) + 6E^{-15} \tag{3}$$

Each equation follows a quadratic function of a second-degree polynomial equation. The dielectric constant is estimated using regression analysis based on the percentage of element data (N, C, and K values). Equation (1) describes the relationship between nitrogen (N) elements and the dielectric constant. Similarly, Eqs. (2) and (3) illustrate the correlation between carbon (C) and potassium (K) elements, respectively, with the dielectric constant. The coefficients in the equations play specific roles in determining the shape and characteristics of the quadratic curve. The N^2, C^2, and K^2 coefficients determine the concavity of the curve, indicating whether it opens upwards or downwards. On the other hand, the N, C, and K coefficients determine the slope or steepness of the curve. These equations can be used to estimate the dielectric constant by substituting different values of nitrogen, carbon, and potassium percentages. By understanding the relationship between elemental composition and dielectric properties, researchers can gain insights into the behavior and performance of dielectric materials in various applications.

Apart from carbon, nitrogen, and potassium, the relationship of the other elemental percentage on the dielectric constant value was difficult to be predicted and concluded. These might be due to the insufficient data or research available on the effect of these elements on the dielectric constant value. In addition, the other elements might not contribute to the dielectric constant value; if so, the contribution might be negligible.

Effect of fiber morphology on dielectric properties

Apart from elemental composition, fiber morphology plays a critical role in determining the dielectric properties of one material. The morphological features can substantially alter the properties and performance of the material since every feature justifies its effect on such material [81]. A study on the morphology of one material could provide essential information for the development of dielectric materials with the desired properties. One could tailor the processing or fabrication conditions during materials development if adequate information on how the materials behave toward treatments is sufficient.

The morphological features of the pineapple leave fibers were investigated by Yusof et al. [81] in terms of fiber diameter and distance between fibers. A clear pictograph of the scanning electron microscope (SEM) images of the pineapple leaf fibers [82] is displayed in Fig. 2. The fiber with the smallest diameter and distance between fibers exhibited the highest dielectric constant value. Meanwhile, the fiber with the largest diameter is shown to produce the lowest dielectric constant value. The reason might be due to the presence of a

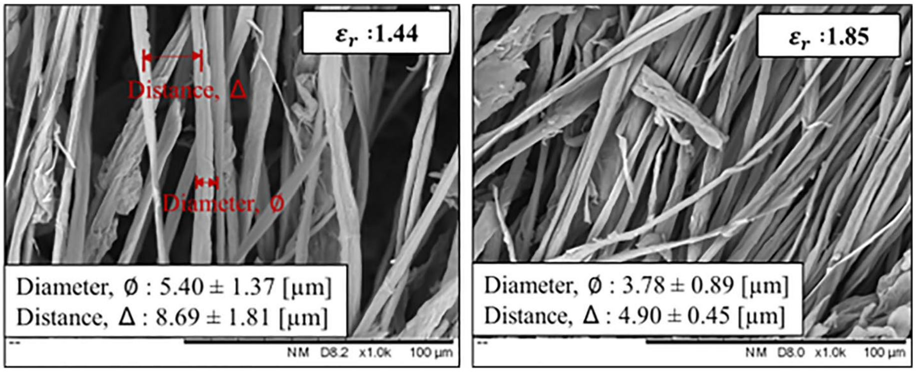

Fig. 2 SEM images for pineapple leaf fiber samples at different diameters and distances between fibers [81]

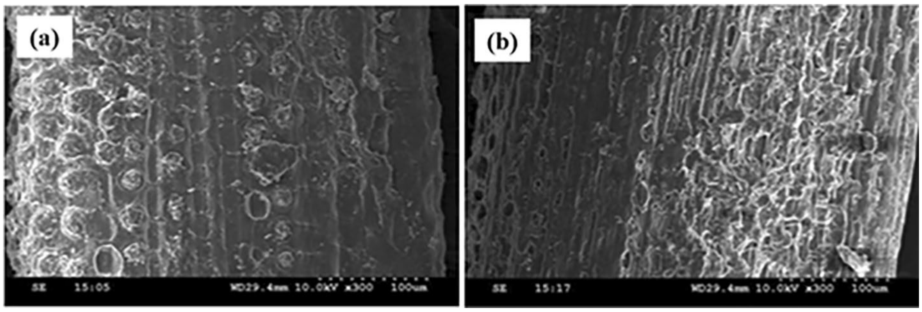

Fig. 3 SEM images of royal palm fibers with **a** untreated and **b** alkali-treated surface [83]

large amount of fiber in the sample with the smallest distance. The increase in fiber concentration could significantly increase the dielectric constant value.

The relationship between surface roughness of the royal palm fiber and dielectric properties was studied by Goud and Rao [83]. The alkali-treated surface of the fiber exhibits a lower dielectric constant value compared to the untreated fiber. As seen in Fig. 3, the surface roughness increases when the fiber is treated with alkali. The increase in roughness has remarkably reduced the ability of the surface to absorb electromagnetic energy, hence reducing the dielectric constant value.

Negi et al. [84] examined the relationship between the morphological structure of the mango leaves in terms of porosity toward its dielectric properties. The dielectric properties of the activated carbon mango leaves were lower than the non-activated leaves. This is due to the formation of pores during the activation process, which significantly alters the dielectric properties of the developed materials. The porous network in the activated carbon mango leaves is observed in Fig. 4. The increase in void spaces causes a decrease in the surface area, which reduces the ability of the material to absorb electromagnetic energy, thereby reducing the dielectric constant value.

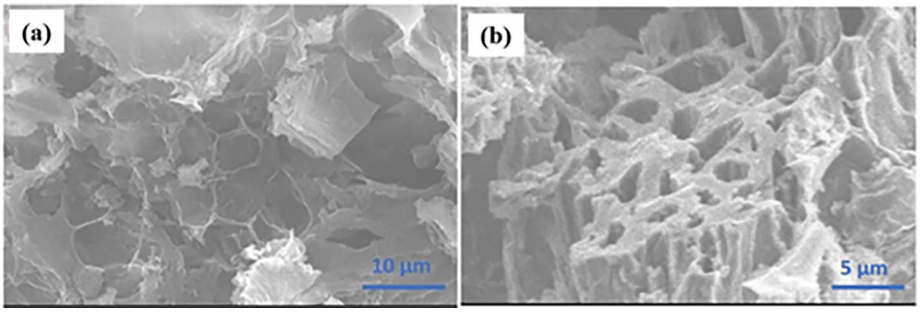

Fig. 4 SEM images of the activated carbon mango leaves with the porous network [84] Reproduced with permission from Elsevier

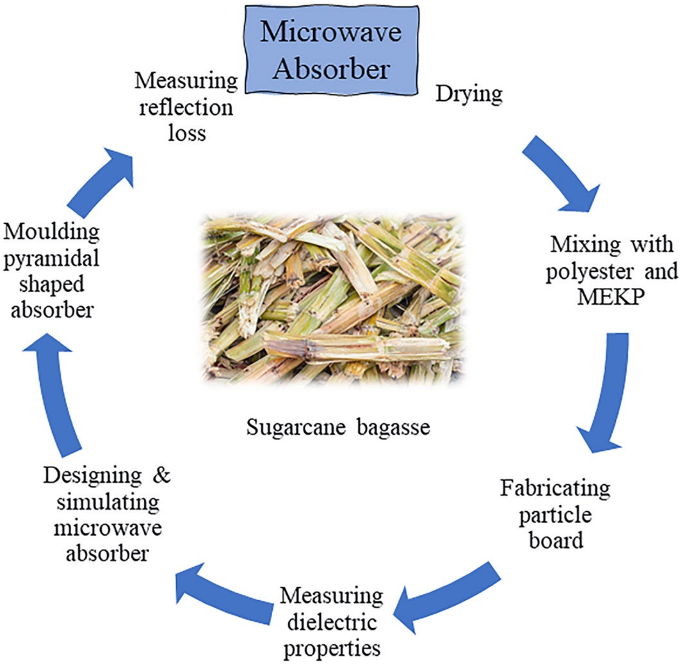

Fig. 5 The fabrication process of sugarcane for microwave absorber [71]

Dielectric materials fabrication

The shape is a crucial characteristic that influences the reflectivity performance of an exemplary microwave absorber. The microwave absorber may be in the various forms of pyramidal, flat, convoluted, wedge, truncated, honeycomb, and oblique. However, absorbers in pyramidal shape are the most commonly applied to develop anechoic chambers due to the least amount of open surface area, which maximizes the absorption of microwave signal [85]. The microwave absorbers available in the market are made from polyurethane or polystyrene, which is plastic foam based. Parameters of this absorber type that need to be considered during designing are the absorber dimension, angle of incidence, material dielectric constant, and carbon coating thickness [71].

Zahid et al. [71] manipulated the sugarcane bagasse to develop a pyramidal microwave absorber, as shown in Fig. 5. The raw sugarcane bagasse was collected and dried before being cut into smaller fragments and ground into tiny particles. The sugarcane bagasse was then mixed with methyl ethyl ketone peroxide (MEKP) and polyester resin, and the particleboard was fabricated using the hot press machine. The particleboard made of sugarcane bagasse was measured for dielectric properties, and the microwave absorber was designed and simulated using the measurement values. The hand press machine and a mold were used to manufacture the microwave absorber in the pyramidal shape before being measured for the reflection loss using the cross-section method.

Kaur et al. [85] applied the same fabrication processes as Zahid [71] but used dried banana leaves and the pyramid-shaped mold was prepared using aluminum foil. The sample was tested for dielectric properties, and the reflection loss was measured by a network analyzer, as stated in the block diagram in Fig. 6. Hossain and Roy [86] used rice husk ash and chicken eggshells to produce synthetic wollastonite. Figure 7 shows the process for wollastonite preparation. The eggshells were crushed and dried, milling to produce the eggshell powder. The collected rice husk was heated to eliminate the volatile matter and carbon compound. The polyvinyl alcohol (PVA) of 3 wt.% was used as a binding agent to form the pellet and was pressed by the hydraulic press. Figure 8 summarizes the procedure for sample preparation using rice husk, banana leaf and sugarcane bagasse.

Zulkifli et al. [36] used the Epoxy Der 331 resin as a hardener agent for rice straw, rice husk, banana leaves, and sugarcane bagasse. The collected materials were ground to get smaller particles to ensure the materials were bound together with the chemicals. Polyamine hardener was supplemented to make the sample solid. The mixture was placed in a rectangular-shaped mold to obtain the preferred shape and hardened at room temperature for two to three days. Danewalia et al. [35] used rice husk and

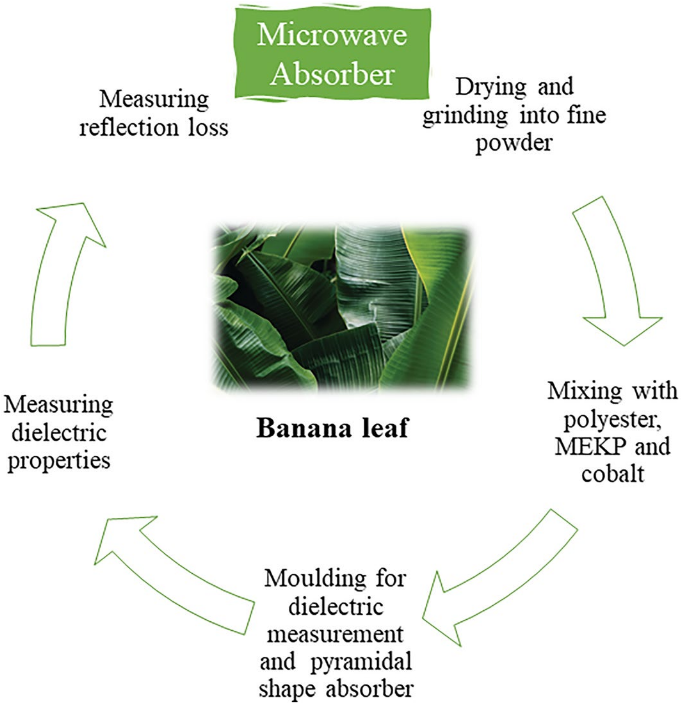

Fig. 6 The fabrication process of banana leaves for microwave absorbers [85]

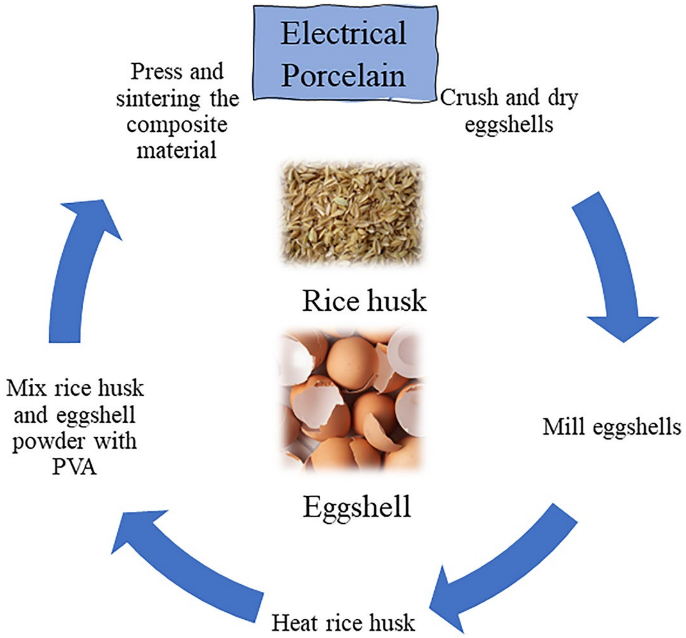

Fig. 7 Fabrication process of rice husk and eggshells for electrical porcelain [86]

Fig. 8 Fabrication process of rice husk, banana leaf and sugarcane bagasse for microwave absorber [36]

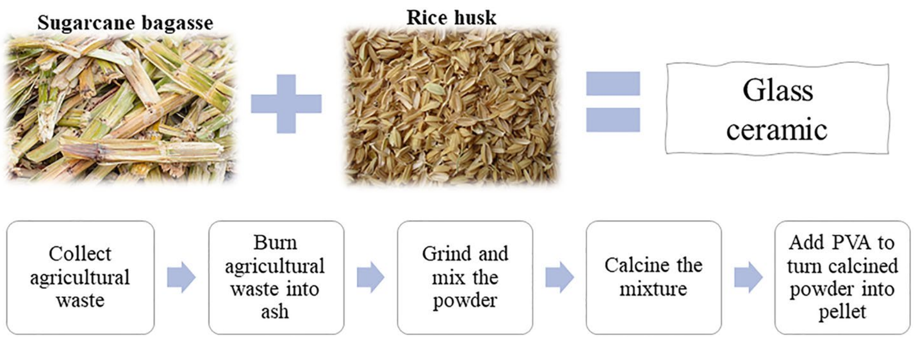

Fig. 9 Fabrication process of rice husk and sugarcane bagasse for glass ceramics [35]

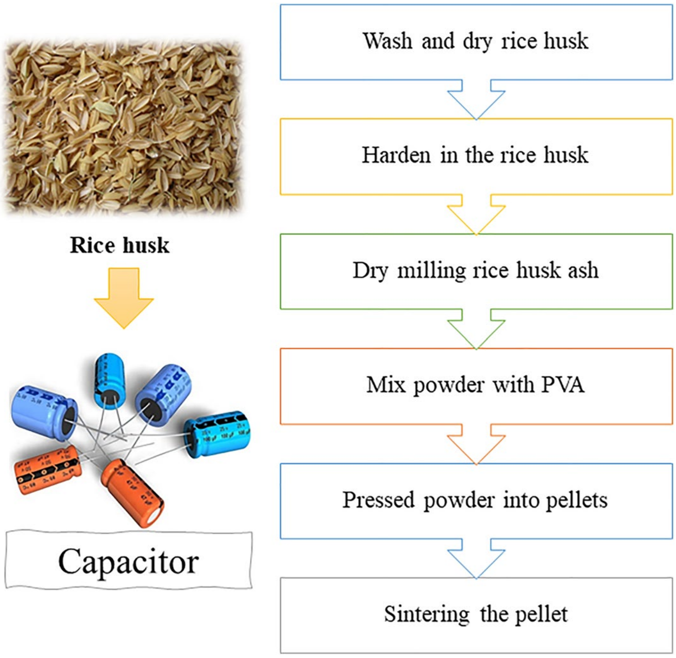

Fig. 10 The fabrication process of rice husk for capacitor [87]

sugarcane leaves as raw materials to produce glass ceramics. The collected samples were burnt to convert into ash. The samples were ground and mixed for homogenization and were calcined. The produced calcined powder was turned into pellets using PVA as a binder agent using a hydraulic press. Figure 9 illustrates the process of creating the powder for glass ceramics.

Osman et al. [87] evaluated the dielectric properties of ceramic materials acquired from rice husks for electronic applications. Figure 10 provides a visual representation of the steps involved in creating pellets from rice husk. The process started by washing and drying the rice husk to eliminate moisture before being placed in a crucible and hardened in the oven at 900 °C for six hours to obtain white ash. The ash was dry-milled in a high-energy ball milling with a hardened steel vial for 20 min using a SPEX 800D mill to get a nano-sized rice husk powder. The obtained white powder was mixed with PVA and pressed into pellets using a hydraulic press machine before being sintered at various temperatures for six hours.

Mahmud et al. [88] used palm oil-based polyurethane and empty fruit bunch (EFB) as a natural filler to design the microwave substrate. The dielectric and structural properties of polyurethane palm oil-based filled empty fruit bunch were evaluated. Figure 11 shows the preparation of empty fruit bunch (EFB) powder started with dried EFB for seven days and ground. The grounded empty fruit bunch was sieved for powder separation before being soaked for 24 h in water to eliminate ash. The EFB was dried until a constant mass was obtained. The polyurethane was made from the exothermic reaction between Diphenylmethane-4,4’-diisocyanate (p-MDI) and glycerol palm oil-based. The polyurethane was finely grounded and mixed with EFB powder to prepare the polyurethane-empty fruit bunch composite. The powder mixture was thoroughly mixed and placed in a rectangular-shaped mold with the X-band dimension mold size. The composite was heated with a hot press before undergoing a curing process until a constant mass was obtained.

Jabal et al. [43] evaluated the dielectric properties of coconut shell activated carbon and coconut shell powder. The fabrication process is illustrated in Fig. 12. The raw coconut shell was cleaned, dried, and sanded into a fine powder. The coconut shell powder was mixed with epoxy resin and stirred by a digital stirrer for one hour and was fabricated using a rectangular mold. Pattanayak et al. [45] applied corn husk to enhance the microwave absorption performance of corn husk-based microwave absorbers. Figure 13 depicts a step-by-step illustration of the corn husk fabrication process. The green corn husks were collected before being dried under the sun for three to four weeks. The dried corn husks were grounded, and the particle was mixed with charcoal powder of different weight percentages before being exposed to ultrasound to ensure optimum homogeneity of the composite. The polyester resin was used as a binder to fabricate a flat-shaped mold, and methyl ethyl ketone peroxide (MEKP) was applied as a hardener. Meanwhile, a cobalt solution was used to work as an accelerator.

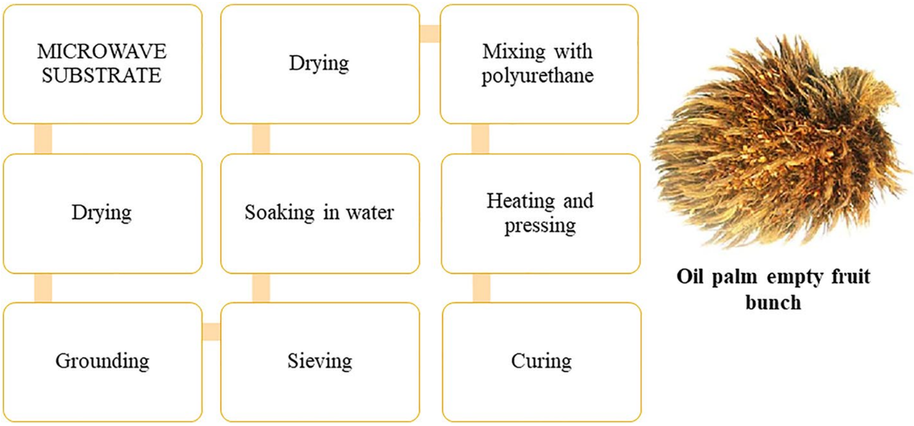

Fig. 11 The fabrication process of dried raw empty fruit bunch powder for microwave substrate [88]

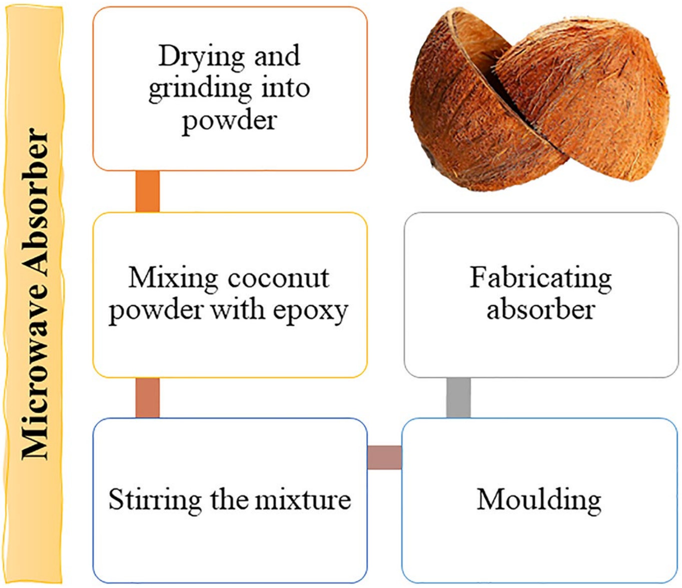

Fig. 12 The fabrication process of coconut shell for absorber [43]

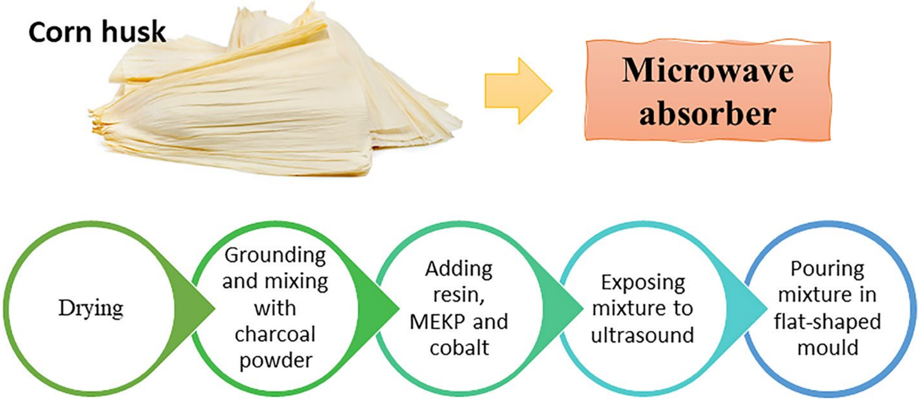

Fig. 13 The fabrication process of corn husk for microwave absorber [62]

Application of dielectric materials from bio-waste

Measuring the dielectric properties of waste materials is the most important parameter in characterizing the physicochemical properties of the storage and loss of energy [36]. The researchers have developed several applications of dielectric materials from agricultural and bio-waste.

Dielectric material as capacitor

Dielectric material was often used for storing energy in capacitors. Dielectric capacitors store electrical energy through an electrostatic field through dielectric polarization. They are often used in pulsed power electronics due to their shorter discharge time and high power density. The type of capacitors was dependent on the dielectric material being used. Polymer, glass, and ceramic are among the dielectric materials proven to store the largest energy [89]. Temeche et al. [90] evaluated the potential of rice husk ash in producing hybrid lithium-ion capacitors electrodes, where the combustion of rice husk produces high surface area silica and carbon. The electrochemical properties of rice husk ash were evaluated by constructing lithium-rice husk ash half-cells and lithium nickel manganese cobalt oxide (NMC)-rice husk ash full-cells. The result shows that both half and full-cell generated a high specific capacitance as opposed to the poor cycle performance of NMC-based batteries at high C-rates. Also, both full and half hybrid cells presented excellent coulombic efficiency (∼100%). The findings imply that rice husk ash could be a possible substitution of electrode material for lithium-ion capacitors with regard to its financial and environmentally friendly characteristics.

Rout et al. [91] measured the dielectric properties of lignocellulosic coirs coated with silver nanoparticles, where the coating had incremented the dielectric constant value and reduced the loss tangent (tan δ). Also, the sintering temperature could go up to 600 °C or more for the silver nanoparticle-coated coir fibers, which are commonly impossible for the embedded capacitors made with low-cost organic polymers for printed circuit boards (PCB) industries. Due to their higher packing density and insulating properties, these coated fibers are considered valuable materials for embedded capacitors, optoelectronic devices, and integrated circuits.

Dielectric material as microwave absorber

Dielectric material was also used as a microwave absorber, with polyurethane as the most common. Microwave absorber was used to reduce the electromagnetic interference (EMI) inside the wireless electronics assemblages since electronics operating at high microwave frequencies may lead to high-frequency noise emission hindering the device's performance. The microwave absorber was an essential element of anechoic chambers for antenna measurements or electromagnetic compatibility (EMC). The interior walls of anechoic chambers were covered by a pyramid-shaped absorber material that functions as wave reflection prevention to devices. The outer walls block the entry of unwanted electromagnetic waves. Some agricultural and bio-wastes were identified to have great potential as excellent microwave absorbers.

Zulkifli et al. [36] applied rice straw, rice husk, banana leaves, and sugar cane bagasse for the microwave application of a microwave absorber. The findings suggest that the reading of dielectric properties increased with the filler percentage. The dielectric constant reading was varied, but banana leaves exhibited the highest with a 4.221 dielectric constant and 0.149 tangent loss at 50% filler. Agricultural waste high in carbon compounds was the most suitable to be applied as a microwave absorber. Carbon and inorganic oxides are the elements that demonstrate excellent dielectric properties with a high loss tangent value [92]. The increase in the carbon compound influenced the increase in dielectric properties. These were due to the ability of carbon for electrical energy storage from microwaves [93]. Simón et al. [94] emphasized that carbon promotes the absorption of electromagnetic waves in the microwave region. The high reading of loss tangent is suited for microwave absorbers in anechoic chambers. Simón et al. [94] evaluated the performance of agricultural wastes of cactus pear, aloe, and coconut shell husk as microwave absorbers, to determine the best material as the absorber. The result shows aloe is the best microwave absorber, with a maximum absorption coefficient of 0.5792 at 9.706 GHz. Compared to polyurethane

(0.1965), cactus pear exhibits better absorbing performance with an absorption coefficient value of 0.2295.

Dielectric material as antenna

The presence of silica in the agricultural waste material reduces the tangent loss of a material where the low tangent loss with a high dielectric constant was suitable for antenna application. Zulkifli et al. [36] evaluated the dielectric properties of rice straw, rice husk, banana leaves, and sugarcane bagasse for antenna application with different filler percentages. Among all wastes, banana leaves exhibited the highest dielectric constant and low loss tangent reading with a 10% filler percentage, making it the most ideal for antenna application than the other type of waste material.

Dielectric material as electrical insulator

In a recent study by Sharma and Singh [95], the application of agri-food wastes in the production of glasses and glass ceramics was proven to be better than the one synthesized by mineral oxides. The dielectric constant of the samples ranged from 10 to 32 at room temperature. Hossain and Roy [86] applied rice husk ash and chicken eggshells to fabricate synthetic wollastonite. The results have shown that a stable and low dielectric constant of 4.5 to 6, losses of 0.0026 to 0.00361, and resistivity of around $6–9 \times 10^8$ (Ω-cm) at 100 kHz was obtained. These findings indicate that waste-derived synthetic wollastonite may be functional as an ingredient in electrical porcelain insulator applications.

Dielectric material as printed circuit board

The need to satisfy the numerous complex tradeoffs involved in electronic devices urged the innovations in ceramic technology, which suited microwave circuit technology requirements for wireless applications due to their superior electrical, electromechanical, thermal, and dielectric performance properties. To produce a high-speed printed circuit board (PCB), the board should possess a high dielectric constant while the loss tangent is lower than 0.004. Wee et al. [54] evaluated the probable substitution material for conventional PCB laminate materials by using paddy waste of rice straw and rice husk. The paddy waste particle board was fabricated using two bonding agents of phenol formaldehyde (PF) and urea–formaldehyde (UF) resins into a rectangular-shaped mold. The result shows that the dielectric constant value varied across different types of resins being used. The dielectric constant of rice husk with PF resins exhibits a higher dielectric constant value than UF resins. Also, by comparing the rice straw and rice husk, the rice husk displayed better dielectric properties, with a higher dielectric constant value [54]. An increase in resin percentage had caused an increase in dielectric properties due to a more volume portion of the resin in the composite. The dielectric properties exhibited by the paddy waste were of comparable performance to the conventional PCB laminates and hence can be a sustainable and renewable solution to the high-cost PCB laminates available in the market.

Summary

This review provides information on the potential use of several bio-waste and agricultural wastes in the production of dielectric materials. The fabrication process and potential applications for each material have been provided and discussed in detail. The analysis of the elemental composition of the waste materials suggests that each element is responsible for determining the dielectric properties of one material. Based on the literature above, bio-waste and agricultural waste could be potent dielectric materials. Processing techniques were observed to be a crucial indicator in producing dielectric materials for specific applications. The processing parameters, such as temperature, chemical treatment, and extraction procedures, could significantly affect the dielectric properties of the developed materials. Modifying these parameters during the material development could help produce dielectric materials with the desired properties.

The development of dielectric materials using bio-waste and agricultural waste could significantly reduce the stress on the environment since these wastes are properly being used to produce valuable materials. The outstanding properties of each material over conventional materials have attracted much novel research to produce materials with great properties. However, several challenges and limitations associated with the production of dielectric material using these wastes should be taken into consideration. Even though these wastes are abundantly and sustainably available, one should not neglect the potential limitation of the waste supply. This is due to uncontrolled external factors such as natural disaster, which might devastate the plantation where the waste is collected, thus limiting the supply of the waste.

Limited storage capacity is another challenge that needs to be addressed. Since collections of materials are usually in bulk, larger storage is required, and not to mention proper storage is necessary since the materials are prone to natural degradation. Improper storage could ruin the fiber composition due to microbial infection. In terms of product disposal, since the materials are made from natural sources, disposal of these materials would be easier due to their biodegradability properties. Also, it is important to consider the long-term durability and stability of the developed dielectric material from bio-wastes. It is recommended to examine its performance under various environmental conditions, including exposure to various chemicals, temperature variations, and humidity levels. The potential of agricultural and bio-waste materials for engineering applications, particularly as microwave signal absorbers, has been discussed and summarized in Table 2.

Conclusion

This review emphasizes the beneficial innovation of bio-wastes and agricultural wastes in developing dielectric materials as substitutes for conventionally used dielectric materials. The elemental composition and morphological features of a material can significantly affect the dielectric properties of the developed material. The use of bio-waste materials not only protects the environment but also helps reduce carcinogenic e-waste. Future studies on the durability of the produced materials could contribute to the investigation of their lifespan in real-life applications. The efficacy of bio-waste as a dielectric material has been proven through this study; hence, its application should be broadened in any field to maximize its role as a valuable yet inexpensive material.

Table 2 Characteristics and applications of agricultural waste materials

Agricultural waste	Material	Carbon composition (%)	Dielectric constant	Estimation cost ($)	Application
Rice straw [36]	1. Rice straw 2. Epoxy Der 331 3. Polyamine clear hardener	38.24	3.231	8.18	Cosmetic Medicine Building material Insulation board Fine chemical Biopolymer
Oil palm empty fruit bunch [88]	1. Empty fruit bunch 2. Palm oil 3. Diphenylmethane-4,4′-diisocyanate (p-MDI) 4. Distilled water	46.83	3.455	31.2	Microwave absorber
Sugarcane bagasse [36]	1. Sugarcane bagasse 2. Epoxy Der 331 3. Polyamine clear hardener	17.89	2.791	8.18	Microwave absorber Pulp Building boards
Coconut shell [43]	1. Coconut shell 2. Coconut shell activated carbon 3. Epoxy resin	53.88	3.769	33.56	Concrete Absorbent
Corn husk [45]	1. Corn husk 2. Charcoal powder 3. Polyester resin 4. Methyl ethyl ketone peroxide (MEKP) 5. Cobalt	54.99	3.9	47.01	Glass Porcelain Resin Paper Films Microwave absorber
Rice husk [36]	1. Rice husk 2. Epoxy Der 331 3. Polyamine clear hardener	35.77	2.982	8.18	Microwave absorber Circuit board Microelectronic Electronic device
Eggshell [86]	1. Chicken eggshells 2. Rice husk 3. Polyvinyl alcohol (PVA)	NA	4.62	8.02	Porcelain
Banana leaves [85]	1. Dried banana leaves 2. Polyester resin 3. Methyl ethyl ketone peroxide (MEKP) 4. Cobalt	43.5	2.109	27.51	Microwave absorber

Abbreviations

EFB	Empty fruit bunch
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
MEKP	Methyl ethyl ketone peroxide
NMC	Nickel manganese cobalt
OPEFB	Oil palm empty fruit bunch
PCB	Printed circuit board

PF	Phenol–formaldehyde
p-MDI	Diphenylmethane-4,4′-diisocyanate
PVA	Polyvinyl alcohol
UF	Urea–formaldehyde

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Author contributions
The project was proposed and supervised by NZ and MSAK. NM, NHA, and ANA write the initial draft. NHA compiled, reviewed the literature, and edited and revised the manuscript. NZ and MSAK participated in the improvement and finalizing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Competing Interests
The authors declare that there is no conflict of interest in relation to this article.

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