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THE OPTIMIZATION OF BAGASSE LEAF-BASED POROUS CARBON-TIN OXIDE ORGANIC CAPACITOR USING TAGUCHI METHOD

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The object of this study is the carbon-based organic capacitors, derived from bagasse leaves from the Kebon Agung sugar factory, Malang, Jawa Timur, serving as a sustainable precursor material. The challenge of optimizing the performance of bagasse leaf-based organic capacitors has been a significant barrier in advancing sustainable electronic components. This study aims to develop a quality framework for synthesizing these capacitors by systematically optimizing the parameters using the Taguchi method. Traditional methods often lead to inconsistent performance and high variability, making it difficult to achieve reliable results. By applying the Taguchi orthogonal array, this study identified key factors and optimal levels, effectively reducing experimental efforts while ensuring robust performance. The carbonization of bagasse leaves was conducted using direct combustion with thinner and 70% methanol as liquid burners. Capacitance tests revealed stable values ranging from 0.8897 nF to 0.9281 nF across trials, demonstrating consistent and reproducible behavior. Thermal noise evaluation showed slight temperature variations (69.01°C to 72.01°C), indicating the influence of temperature on electron mobility within the dielectric materials. The systematic approach of the Taguchi method minimized variability and enhanced the capacitors' reliability under varying thermal conditions. The method's focus on robustness and quality control ensured consistent capacitance values and improved overall capacitor performance. Compared to traditional methods, the Taguchi method facilitated a thorough exploration of the design space with fewer experiments. This study underscores the importance of systematic optimization in capacitor design, offering a reliable pathway to integrate sustainable materials into advanced electronic components. The results provide valuable insights into the effects of different parameters on performance metrics, enhancing the development of high-quality organic capacitors

Keywords: Taguchi method, bagasse leaves, organic capacitor, tin oxide, dielectric material

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1. Introduction

Biomass waste is one of the most underutilized promising materials for energy resources in Indonesia. The rich agricultural activity in Indonesia generates vast amounts of biomass waste including rice husks, coconut shells, palm oil residues, and bagasse residues. One of the key agricultural sectors in Indonesia is sugarcane industry with approximately 3 million metric ton of production each year [1]. However, not all potential economic benefits already covered in current sugarcane industry by-product utilization scheme. Current utilization of sugarcane byproduct in Indonesia is for animal feed, renewable energy cogeneration plant, and molasses as ingredient for monosodium glutamate, which only cover 90% of bagasse waste utilization [2]. Another 10% of unutilized bagasse waste mainly from its leaf. The sequential pyrolysis method to transform bagasse leaf into carbon nanostructure is still under development and may not stand to the variation in bagasse leaf wastes condition [3]. Therefore, the study of bagasse leaf utilization is important to support zero waste in sugarcane industry.

Recent studies have shown that the sugarcane sector has a considerable negative environmental footprint, with bagasse cogeneration identified as the largest contributor to environmental burdens. Human health accounts for 71.2% of the total impact score due to emissions during combustion, while additional CO_2 emissions arise from the dependence on grid electricity for sugar production, leading to an accumulative effect on climate change and local air quality [4]. At the same time, Indonesia's growing energy demand continues to rely heavily on fossil fuels, further driving CO_2 emissions and environmental degradation [5]. Although renewable resources such as ocean waves and currents have been studied, their potential remains highly seasonal wave energy may peak at around 2.5 GW during certain months, and ocean current energy ranges between 120–150 kW in straits like Makassar and Java making them less suitable as baseline low-CO_2 energy sources [6]. This combined evidence underscores the paradox that while cogeneration is framed as renewable, current sugarcane by-product utilization still lacks sustainability, reinforcing the urgency of developing alternative valorization strategies such as converting bagasse leaves into advanced carbon materials to diversify Indonesia's clean energy portfolio.

The support on zero waste in sugarcane industry could have dual potential in economic and environmental impact. The use of bagasse as a material for cogeneration reveals it energetic traits. This energetic trait makes sugarcane molasses fit for bioethanol production through dark fermentation [7]. However, it was only the molasses from the liquid waste on bagasse straw which leaves another part on its own utilization. The solid part utilized as a bagasse-fired cogeneration plant along with steam powerplant or biomass co-firing to produce renewable electricity with its efficiency can be improved through the application of Kalina cycle [8]. Even the efficiency is largely depends on the steering mechanism of the turbine, the utilization of sugarcane waste as biomass co-firing adds up its value [9]. The chemical processing method has a potential to add bagasse leaf value. Similar method has been performed to optimized coffee's chlorogenic acid (CGA) content by controlling Si to Al ratio in Kereweng traditional roaster [10]. This is solid thermochemical interface solutions which require high temperature to start the chemical reaction. Another solution is using liquid intermediary which enable the reaction to start utilizing polar interaction. One of the implementations was the porous tofu waste interaction when submerged in turmeric powder electrolyte mixture with sodium bicarbonate which enhances the hydrogen production through electrolysis [11]. Therefore, finding the effective route to transform Bagasse leaf into material for energy is crucial.

2. Literature review and problem statement

The paper [12] presents the results of research on biomass-based materials for energy applications, which has gained substantial attention due to the global shift towards sustainable and renewable energy sources. It is shown that biomass-derived carbon materials such as activated carbon from coconut shells, rice husks, and bagasse exhibit excellent electrochemical properties, including high surface area, good electrical conductivity, and environmental benefits, making them suitable for supercapacitors. This work confirmed the high charge storage capacity of biomass carbons, but it also noted challenges in reproducibility due to variations in precursor quality. These properties are largely attributed to the hierarchical pore structures, consisting of macro-, meso-, and micro-porosity, which enhance electrolyte accessibility and charge storage [13]. However, the authors highlighted that pore distribution control remains difficult, which limits consistency across different batches of materials. Furthermore, the incorporation of biopolymers and lignin from biomass into capacitor electrodes has demonstrated improvements in energy density and cyclic stability [14]. While beneficial, this study did not fully address how synthesis conditions influence lignin's role, leaving uncertainties in process optimization. Thus, the literature underscores the dual advantage of utilizing biomass-based materials: offering solutions for waste management while simultaneously advancing sustainable energy storage technologies.

In particular, the carbonization of bagasse leaves represents a promising approach for converting agricultural waste into high-value carbon materials. It is shown that pyrolysis in the range of 400–800°C under an inert atmosphere produces porous carbons with high surface area and good electrical conductivity, while subsequent activation by steam or chemical agents such as KOH further enhances porosity and electrochemical performance [15]. The study demonstrated clear improvements, but it also emphasized the sensitivity of bagasse carbons to pyrolysis conditions, making standardization difficult. These findings demonstrate that bagasse leaf-derived carbons can compete effectively with other biomass-based carbons as sustainable and cost-effective electrode materials [16]. Nonetheless, the authors noted that inconsistent precursor preparation methods remain a major limitation, hindering large-scale applicability. But there are unresolved issues related to the absence of a standard development method for producing energy application materials from bagasse leaves. The reason for this may be the lack of parametrical setup guidelines during synthesis, which prevents systematic control of conditions and the identification of optimum combinations that could improve the electronic properties of the resulting carbon.

A way to overcome these difficulties can be the application of design of experiment (DOE) methods, which enable systematic optimization of synthesis parameters. This approach was used in several studies, with the Taguchi method being one of the most widely adopted DOE frameworks. Originally developed by Genichi Taguchi, this method minimizes variation and identifies optimal conditions with a reduced number of experiments, offering robustness and efficiency [17]. Although effective, its application to biomass materials has so far been limited, leaving a gap in its use for bagasse optimization.

Other optimization frameworks, such as FMEA or multicriteria decision-making, have been tested in different domains but show clear limitations compared to Taguchi. For instance, the Taguchi-Pareto design has been applied in leaf spring parameter optimization, where aspect ratios improved material usage, yet the focus remained on reporting optimal numeric values without systematic parameter control [18]. Similarly, in maintenance engineering, OEE within TPM was used to benchmark machine effectiveness [19]. However, the method emphasized performance measurement rather than robust parameter optimization. In advanced machining, entropy-based multicriteria analysis was adopted for WEDM of Nitinol-60 SMA [20], successfully ranking parameter priorities but remaining descriptive in nature. These approaches, while valuable in their contexts, lack the structured robustness, reduced experimentation, and reproducibility that make Taguchi superior for bagasse-based carbon optimization.

In material and energy research, the Taguchi method has been employed to optimize processes such as biofuel production [21]. Biodiesel was successfully synthesized from inedible castor oil via single-step acid esterification optimized using the L16 Taguchi method, achieving 90.83% free fatty acid (FFA) conversion and fuel properties comparable to petro-diesel within American society for testing and materials (ASTM) standards. This result highlights the Taguchi method efficiency, though the authors noted its dependence on accurate factor selection. Taguchi method also beneficial for photovoltaic cell manufacturing [22]. CuO thin films prepared by sol-gel spin coating and optimized using an L9 Taguchi design exhibited uniform morphology, high visible absorbance with a band gap of 1.47 eV. The work confirmed improved film quality, but also showed limitations in scaling the optimized process beyond lab-scale. In battery development, Taguchi method also shows critical improvement [23]. Using the Taguchi method, the capacity of a 12 V 7.2 Ah lead-acid battery was optimized under varying C-rate, temperature, and humidity, with regression analysis achieving a high predictive accuracy ($R^2 = 97.02\%$). This demonstrated predictive robustness, though experimental validation was still required to confirm long-term performance. These, consistently shows its ability to reduce costs, improve reproducibility, and enhance performance [24]. Still, prior applications have focused mostly on other energy devices, with no direct implementation for bagasse carbons. A review highlights the statistical approaches particularly the Taguchi method focuses mainly on operating conditions (notably heat source temperature) and geometrical configuration (leg height), which significantly influence system performance. However, its application to the development of bagasse leaf-based organic capacitor materials remains unexplored.

All this suggests that it is advisable to conduct a study devoted to the development and optimization of bagasse leaf-based organic capacitor quality using the Taguchi method, thereby addressing the unresolved issues of synthesis standardization and parameter control to improve electrochemical performance.

3. The aim and objectives of the study

The aim of the study is to build a quality development framework for choosing the parameter of the bagasse leaf from sugarcane waste-based organic capacitor. This will make it possible to establish a reliable methodology for selecting synthesis parameters that enhance the performance of organic capacitors derived from sugarcane bagasse leaves.

To achieve this aim, the following objectives were accomplished:

– to design and implement a Taguchi orthogonal array for systematically varying and testing synthesis parameters;

– to experimentally measure capacitance values across parameter sets and determine optimal performance conditions;

– to conduct morphological, structural, and electrochemical analyses to establish property–performance relationships;

– to validate the optimized capacitor by assessing electrochemical stability and overall energy storage performance.

4. Materials and methods

The object of this study is the carbon-based organic capacitors, derived from bagasse leaves from the Kebon Agung sugar factory, Malang, Jawa Timur, serving as a sustainable precursor material.

The hypothesis of the study is the utilization of bagasse leaves as a carbon precursor, combined with systematic parameter optimization using the Taguchi method, will yield organic capacitors with improved electrochemical performance, stability, and cost-effectiveness compared to non-optimized or conventional approaches.

The bagasse leaves were dried following the drying standard ISO 18134-1:2015 [25]. Hence, the leaves were dried in an oven at (105 ± 2)°C until constant mass was achieved. The dried bagasse leaves were uniformly minced to a particle size of following ASTM E1757-01 (standard practice for preparation of biomass for compositional analysis) to ensure consistency in subsequent processing [25]. It is assumed that the composition of bagasse leaves from the Kebon Agung sugar factory is representative of sugarcane leaf waste in Indonesia. It is further assumed that drying at 105 ± 2°C does not significantly alter the intrinsic carbon structure of bagasse leaves beyond moisture removal. Additionally, it is assumed that uncontrolled combustion parameters (temperature and time) reflect the natural variability of traditional carbonization practices.

The carbonization of bagasse leaves was performed through direct combustion with different liquid burners in this study was carried out with thinner and methanol (70% concentration) as fuels, involving a methodical process to create carbon materials. The detail factors involved in parameter tuning can be seen in Table 1. Initially, bagasse leaves were collected, cleaned to remove impurities, and dried by sunbathing for 10 days to reduce moisture content. A combustion chamber or furnace was then prepared, equipped with burners designed for thinner or methanol fuel. During the combustion process, thinner was used to achieve a rapid high-temperature burn. Alternatively, 70% methanol, a simpler alcohol with a slightly lower flame temperature, burns cleanly and results in a slower combustion rate, potentially affecting the carbon's pore structure and surface area. Since the purpose of this stage was to explore natural variation, temperature and time were left uncontrolled to compare natural carbonization parameters, as summarized in Table 1. After combustion, the furnace was gradually cooled to room temperature to prevent further oxidation of the freshly produced carbon material. The carbonized bagasse leaves were then collected.

Table 1

The tuned parameters to obtain optimum organic capacitor from bagasse leaf

Factor	Factor name	Level	
		1	2
A	Width of the material (cm^2)	1	3
B	Bagasse leaf mass (gram)	100	300
C	Volume of the combustion fuel (ml)	100	300
D	Burner media	Ceramic	Metal
E	Times combustion performed	1	3
F	Tin-oxide mass (gram)	18	72
G	Fuel type	Alcohol	Paint-Thinner

The statistical analysis was carried out using Minitab 19 software. The orthogonal array (L8) was generated in Minitab, and experimental responses were entered accordingly. The software was used to calculate signal-to-noise (S/N) ratios for each trial under the "larger-is-better" criterion, suitable for maximizing capacitance. Factor effects and main effects plots were generated to visualize influence trends. Analysis of variance (ANOVA) was performed within Minitab to quantify the percentage contribution of each factor and determine significance at a 95% confidence level. The optimal factor combination was identified by combining the highest S/N ratio with statistically significant factors, and confirmation runs were validated in Minitab by comparing predicted vs. experimental values.

The organic capacitor performance test of carbonized bagasse leaf was performed after the synthesis process. The experimental setup of the capacitance value measurement can be viewed in Fig. 1. Tin oxide (SnO_2) gum was used as the main dielectric material to support the test. The bagasse leaf carbon was placed on top of the heated tin oxide gum until 70°C. The material then attached in between of a Zinc and Copper charger-discharger plate. The Zinc charger attached to 5V Arduino UNO R3 microcontroller pin to obtain voltage and current. The copper attached to the ground to directly discharge the capacitor. This forms a charge-discharge cycle which can be measured based on voltage difference in Arduino UNO R3 microcontroller. The temperature of the organic capacitor gum was measured using LM35 sensor attached to the side of the gum. The performance testing setup was designed with reference to international practices. Although a custom test rig was used, the charge–discharge evaluation follows principles comparable to IEC 62391 (Fixed capacitors for use in electronic equipment) and ASTM D150 (dielectric properties of materials) [26, 27]. These analogues were considered to ensure comparability with international capacitor testing standards.

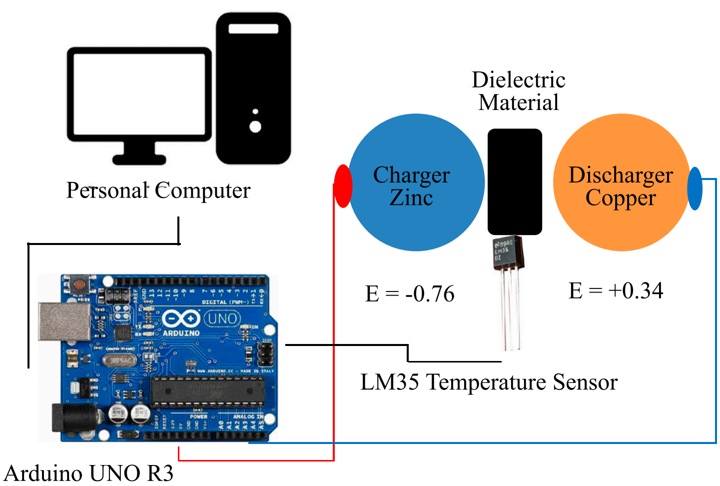


Fig. 1. The setup to measure the capacitance of organic capacitor from bagasse leaf

The Taguchi method was applied to develop the quality of organic capacitor from bagasse leaf. The step to identify the optimal design parameters started by finding the key factors affecting capacitor performance. Next, a series of controlled experiments are designed using an orthogonal array, which allows for the examination of multiple factors with a minimal number of experiments in this case 8 factors. Each experiment tests different combinations of factor levels to assess their impact on performance metrics like capacitance, energy density, and cyclic stability. The results are then analyzed using signal-to-noise (S/N) ratios to determine the robustness of each combination against variability. Statistical analysis, such as Analysis of variance (ANOVA), is used to quantify the significance of each factor. The optimal settings for the highest quality capacitor are identified based on the combination that maximizes desired performance characteristics while minimizing undesirable variations. This method ensures a thorough exploration of the design space with reduced experimental effort, leading to efficient and reliable improvement in the quality of organic capacitors.

The surface morphology of the carbon materials was analyzed using a scanning electron microscope (SEM) FEI Quanta. Prior to imaging, the samples were coated with a thin layer of gold to enhance conductivity and prevent charging under the electron beam. SEM observations were conducted at various magnifications to examine pore development, surface roughness, and structural changes induced by the combustion process. The high-resolution imaging allowed a detailed comparison between the pristine and composite carbon samples. This follows conventional SEM preparation protocols as recommended in ISO 16700:2016 (Microscopy of carbonaceous materials) [28].

Functional group identification was carried out using a Fourier transform infrared spectrometer (FTIR) Shimadzu. The samples were ground with potassium bromide (KBr) and pressed into pellets for analysis in the 400–4000 cm^{-1} wavelength range. The FTIR spectra were used to detect characteristic absorption bands corresponding to oxygen-containing groups, hydrocarbons, and other surface functionalities. This analysis provided insight into the chemical interactions between bagasse leaf carbon and tin oxide. The FTIR procedure is aligned with ASTM E1252 (infrared spectroscopic analysis of carbon materials) [29].

To investigate the volatile components and combustion residues, gas chromatography-mass spectrometry (GC-MS) was conducted using a Shimadzu instrument. The solid carbon samples were subjected to pyrolysis, and the resulting volatile compounds were separated and identified based on their retention time and mass spectra. This technique enabled the identification of organic compounds potentially influencing the electrochemical performance. The GC-MS data complemented the morphological and chemical characterization results. The GC-MS method is comparable to ASTM D1945/D1946 standards for hydrocarbon analysis [30].

5. The results of quality development framework building for bagasse leaf organic capacitor synthesis

5. 1. The result of Taguchi orthogonal array factor and level factor analysis

The combination of each factor for the optimum capacitance determination of bagasse leaf organic capacitor is determined through orthogonal array. According to the 8 factors 2 levels (L8) Taguchi orthogonal array, the combination is arranged as in table 2. Each alphabet in the table row head represents the factors and the number inside the cell represents the level factor. The selected factors capacitor width (A), bagasse leaf mass (B), volume of burner liquid (C), combustion chamber material (D), burning frequency (E), mass of mixture (F), and types of burner liquid (G). The option on each factor (level factor) is 2 which arranged with combination in the cell of Table 2.

The application of Taguchi method reduces the amount of experiment required to obtain the general portrait of the results. In this study, the use of L8 orthogonal array helps to arrange the best combination which representative for overall synthesis of the organic capacitor. The application of Taguchi orthogonal array prevents the full experimental approach which involves 64 of level factor combinations. Therefore, the Taguchi orthogonal array as DOE largely improves the efficiency of the organic capacitor synthesis process.

Table 2

The applied trial combination based on the Taguchi factor determination

Trial	Factor						
	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

5. 2. The result of optimum capacitance value from the performance test

The organic capacitor test results, obtained using eight different Level factor combinations across various trials (Trial 1, Trial 2, Trial 3, Trial 4, Trial 5, Trial 6, Trial 7, and Trial 8) reported in Fig. 2, show consistent and closely clustered capacitance values in nanofarads (nF). The capacitance readings range from a minimum of 0.8897 nF to a maximum of 0.9281 nF, demonstrating stable performance for each dielectric material. Most readings hover around the 0.9 nF mark, showing minor fluctuations across different trials. The uniformity of the results suggests reliable and reproducible behavior of the bagasse leaf-based organic capacitors, regardless of the dielectric material used under the given test conditions. The best combinations indicated by combination rank in Fig.2.

The capacitance test result also suggests the Taguchi method, which utilizes a systematic and statistical approach for optimizing processes and improving quality, likely contributed to the consistent and closely clustered capacitance values observed in the test results. The careful selection of different dielectric materials combination as level factors, the method ensures a robust design that minimizes variability and enhances the reliability of the capacitors. The minor fluctuations in capacitance values suggest that the Taguchi method effectively identified optimal combinations, leading to stable performance across different trials. This approach helps in identifying the best material combinations that result in the most consistent and reproducible bagasse leaf organic capacitor behavior under varying conditions.

5. 3. The result of morphological, structural, and electrochemical characterization

Gas chromatography-mass spectrometry (GC-MS) analysis of the bagasse leaf-based porous carbon sample in Fig. 3 revealed the presence of multiple chemical constituents, with the chromatogram displaying nine major peaks between 4.0 and 19.0 minutes of retention time. The most dominant peak (Peak 5) appeared at approximately 12.5 minutes, with an intensity exceeding 91 million counts, indicating a highly abundant compound within the sample matrix. Peaks 7 and 8, observed at around 12.8 and 13.0 minutes respectively, also exhibited substantial intensities, signifying their relevance as major constituents. In addition to these, numerous smaller and unresolved peaks were detected, particularly within the 8.0–11.5 minute and post-13.5 minute windows, suggesting the presence of less concentrated or structurally complex compounds. These chromatographic features confirm that the carbon-tin oxide composite derived from bagasse leaves contains a diverse mixture of organic compounds, likely resulting from the carbonization and activation processes. The subsequent mass spectral data would enable further identification of these molecular species, providing critical insights into the chemical composition and functional groups contributing to the material's electrochemical behavior in the organic capacitor.

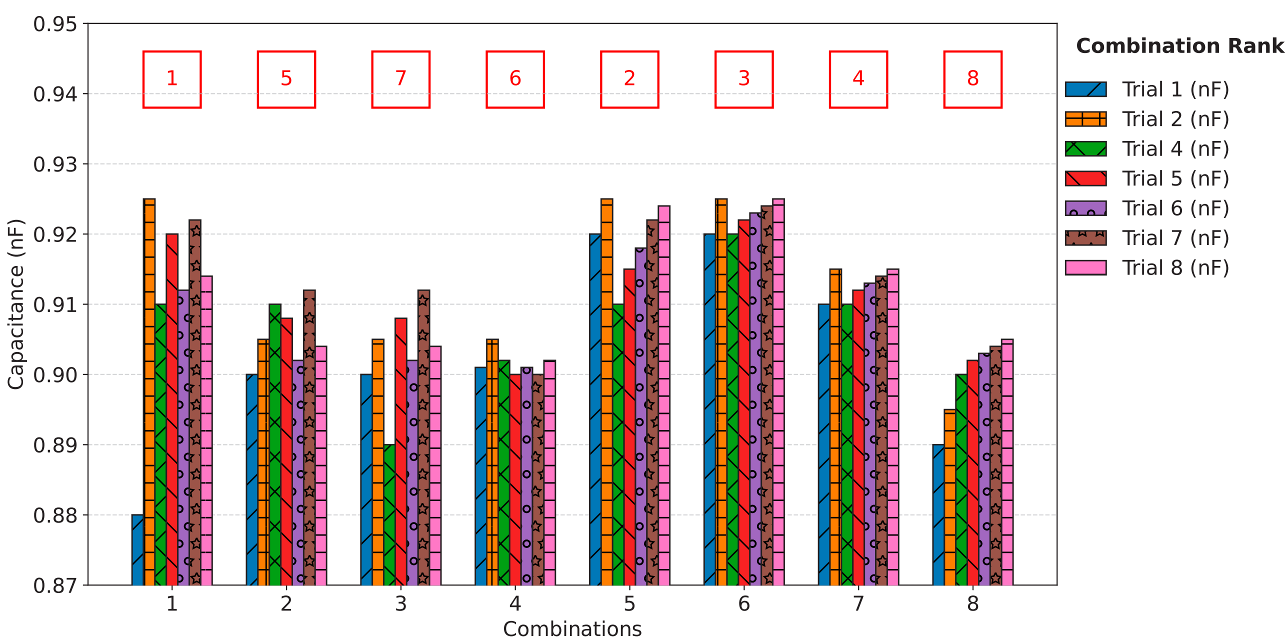


Fig. 2. The graphical result of bagasse leaf organic capacitor testing

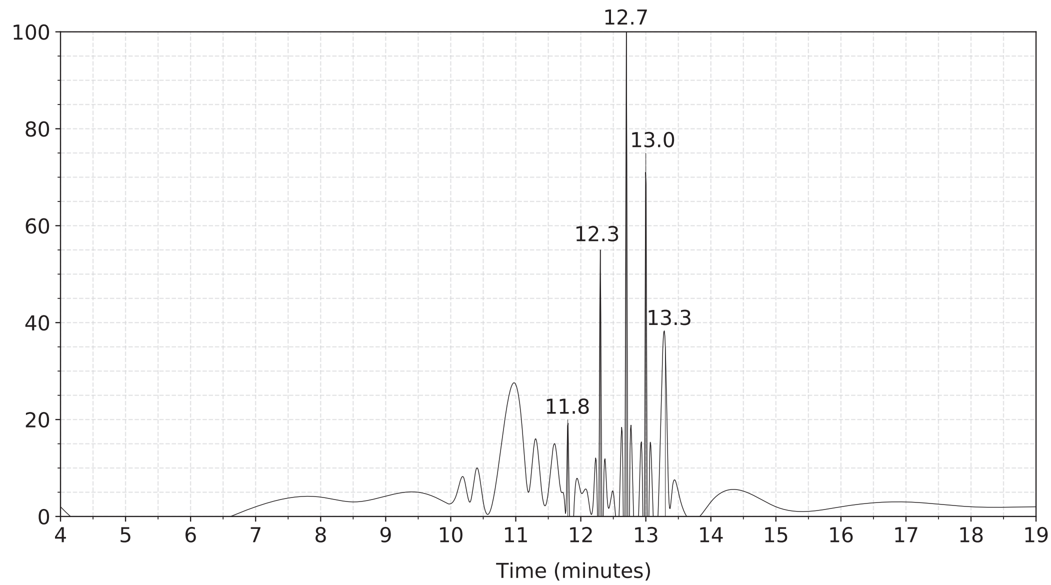


Fig. 3. The gas chromatography spectroscopy result of the bagasse leaf carbon as the organic capacitor dielectric material

The FTIR spectrum in Fig. 4 of the bagasse leaf-derived carbon reveals a diverse array of functional groups, indicating incomplete carbonization and the preservation of organic moieties inherent to the biomass precursor. A broad and intense absorption band observed at 3395 cm^{-1} corresponds to O–H stretching vibrations, suggestive of hydroxyl groups, likely originating from adsorbed moisture and residual lignocellulosic compounds such as cellulose or lignin. The peaks at 2920 and 2853 cm^{-1} are attributed to aliphatic C–H stretching vibrations, indicating the presence of saturated hydrocarbon chains. A weak band at 1728 cm^{-1} is assigned to C=O stretching from carboxylic or ketonic groups, supporting the retention of oxygenated functionalities, which is also commonly reported in partially carbonized biomass [31]. A distinct absorption at 1638 cm^{-1} suggests C=C stretching from aromatic rings, reflective of the lignin-derived aromatic structure in the charred material. Further characteristic peaks at 1428, 1376, and 1322 cm^{-1} indicate C–H bending and possible C–O stretching, while the strong absorptions at 1162 and 1048 cm^{-1} are associated with C–O stretching from alcohols or ethers. Below 900 cm^{-1}, the presence of peaks at 899, 784, 664, and 566 cm^{-1} are indicative of aromatic C–H out-of-plane bending and complex skeletal vibrations, confirming aromatic substitution patterns [32]. The fingerprint region (1500–500 cm^{-1}) serves as a diagnostic tool to verify the retention of lignocellulosic features in carbon materials. Overall, the FTIR analysis confirms that the bagasse leaf carbon retains significant organic and oxygen-containing functionalities, suggests that the carbonization process was sufficient for partial graphitization but not complete deoxygenation, which may positively influence electrochemical behavior in capacitor applications due to pseudocapacitive contributions.

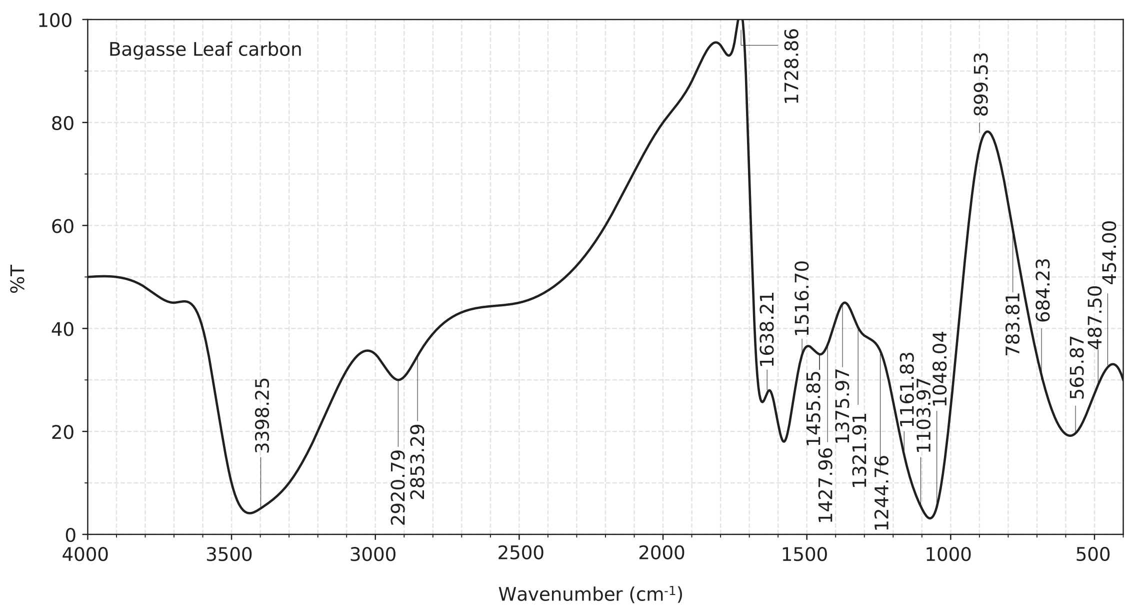
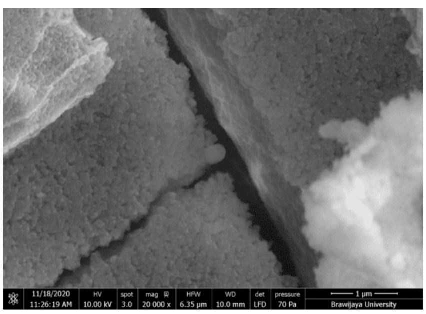


Fig. 4. The Fourier transform infrared spectroscopy result of the bagasse leaf carbon as the organic capacitor dielectric material

The surface morphology of the synthesized tin oxide (SnO_2) material examined using SEM is shown in Fig. 5, with micrographs captured at two distinct magnifications to reveal both macro- and nano-scale structural features. At lower magnification (*a*, 20,000×, scale bar: 1 μm), the SnO_2 structure exhibits a porous, sponge-like network composed of interconnected nanoparticles forming large agglomerates with visible fractures and voids. The rough and irregular surface suggests that the tin oxide has undergone aggregation, likely during synthesis or drying, leading to the formation of cracks within the bulk material. A higher magnification image (*b*, 50,000×, scale bar: 500 nm) reveals greater structural detail, highlighting individual spherical to semi-spherical nanoparticles distributed throughout the porous framework. The presence of interparticle voids and open channels is clearly evident, indicating a high degree of porosity. This hierarchical nanostructure characterized by nanoparticle clustering and abundant mesoporous channel is highly favorable for electrochemical applications such as capacitors, where increased surface area facilitates enhanced electrolyte interaction and charge storage. The multi-scale structural insights provided by Fig. 5, *a*, *b* confirm that the SnO_2 component of the composite offers an ideal architecture for improving ion accessibility and optimizing the double-layer and pseudocapacitive behavior in the organic capacitor system.



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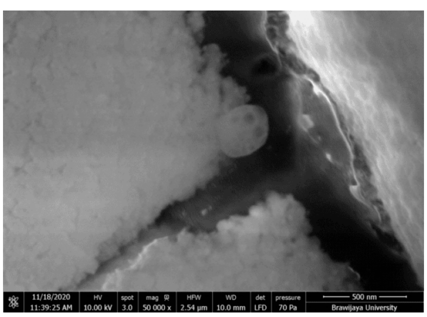
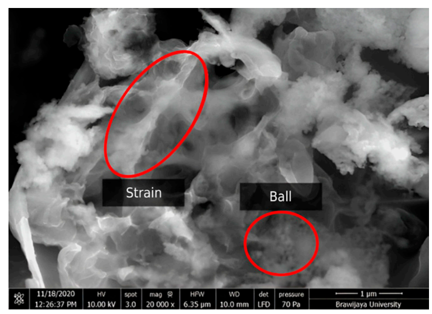


b

Fig. 5. The Scanning electron microscope image of the tin-oxide as the dielectric template material:
a – 20.000x magnification; *b* – 50.000x magnification

Fig. 6 shows the SEM micrographs of the bagasse leaf-derived porous carbon-tin oxide (SnO_2) composite at varying magnifications. In Fig. 6, *a* (20,000×, scale bar: 1 μm), two distinct morphologies are visible: large, crumpled, layered structures labeled as "strain," corresponding to the carbon matrix, and smaller, brighter spherical particles labeled as "ball," corresponding to agglomerated SnO_2 nanoparticles embedded on the carbon sheets. Fig. 6, *b* (50,000×, scale bar: 500 nm) provides a closer view of the intertwined structure, where the carbon matrix appears wavy and porous, and SnO_2 particles are dispersed as bright clusters across the surface. Fig. 6, *c* (100,000×, scale bar: 200 nm) reveals fine details of the composite, including a sponge-like carbon texture with nanoscale pores and SnO_2 nanoparticles distributed within the porous network. These images confirm the successful formation of a hierarchical porous composite structure with distinct carbon and tin oxide domains.

The SEM analysis reveals that pure SnO_2 exhibits a porous, sponge-like network of interconnected nanoparticles forming large agglomerates with fractures and voids, while higher magnification highlights spherical to semi-spherical nanoparticles and abundant mesoporous channels that enhance surface area and ion accessibility, making it suitable for electrochemical applications. In the bagasse leaf-derived porous carbon-SnO_2 composite, two distinct morphologies are observed: crumpled, layered carbon structures and smaller bright SnO_2 nanoparticles embedded within the carbon matrix. At increasing magnifications, the composite displays a wavy, porous carbon framework with well-dispersed SnO_2 clusters and nanoscale pores, confirming the successful integration of hierarchical porous carbon and tin oxide domains. This architecture provides high surface area, interconnected channels, and favorable electrochemical characteristics for organic capacitor performance.



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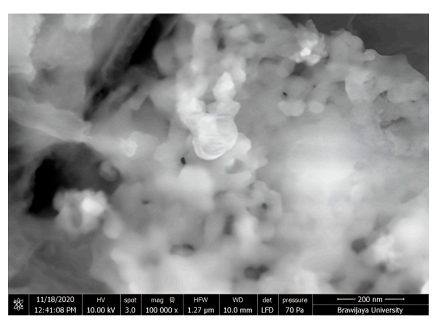


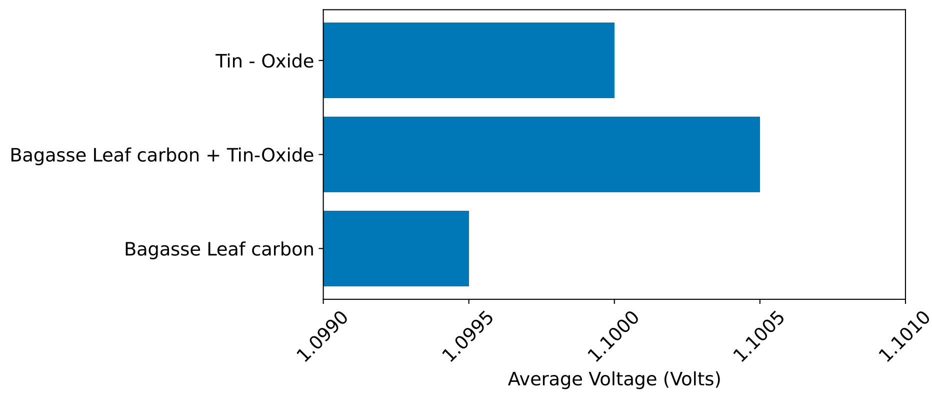
c

Fig. 6. The scanning electron microscope image of the tin-oxide as the dielectric template material:
a – 20.000x magnification; *b* – 50.000x magnification;
c – 100.000x magnification

5. 4. The result of performance evaluation

Fig. 7 presents the performance evaluation of the bagasse leaf porous carbon-tin oxide organic capacitor, based on average voltage and holding current measurements for three different electrode configurations. In Fig. 7, *a*, the composite electrode of bagasse leaf carbon with tin oxide exhibits the highest average voltage at 1.1005 V, followed by pure tin oxide at 1.1000 V, and pure bagasse leaf carbon at 1.0993 V. In contrast, Fig. 7, *b* shows that the highest average holding current is observed in the tin oxide electrode (1.0 mA), followed by bagasse leaf carbon (0.95 mA), while the composite material shows the lowest value at 0.45 mA. These results indicate that the composite electrode enhances average voltage but reduces current holding capability compared to the individual components.

The dielectric temperature fluctuations observed from the four best capacitance values show a range of temperatures across different trials. The recorded temperatures are as follows: 70.19°C, 71.45°C, 69.99°C, 70.1°C in T1; 70.41°C, 69.41°C, 71.22°C, 69.18°C in T2; 70.32°C, 70.02°C, 70.16°C, 69.81°C in T3; and 69.44°C, 71.27°C, 70.33°C, 70.52°C in T4 visualized in Fig. 8. These temperatures exhibit slight variations, generally fluctuating around the 70°C mark. The data shows that, while temperatures are relatively consistent, there are minor deviations in each trial, with temperatures ranging from a low of 69.01°C to a high of 72.01°C. This indicates while the capacitance performance is stable, there are small differences in thermal behavior across the level factor combination.



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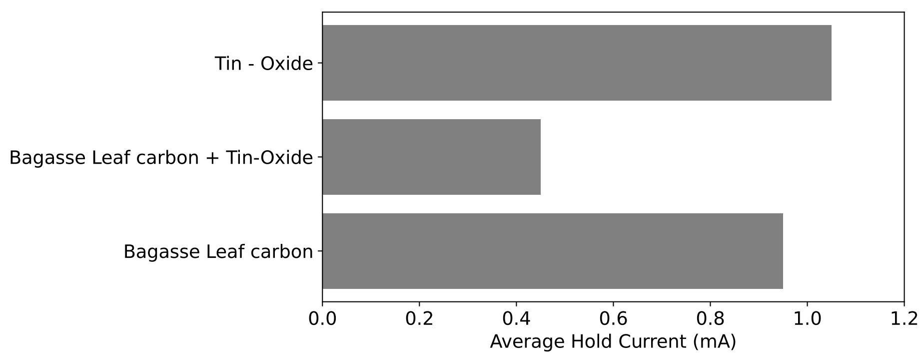

b

Fig. 7. The performance evaluation of bagasse leaf porous carbon-tin-oxide organic capacitor based on: *a* – average voltage; *b* – average holding current

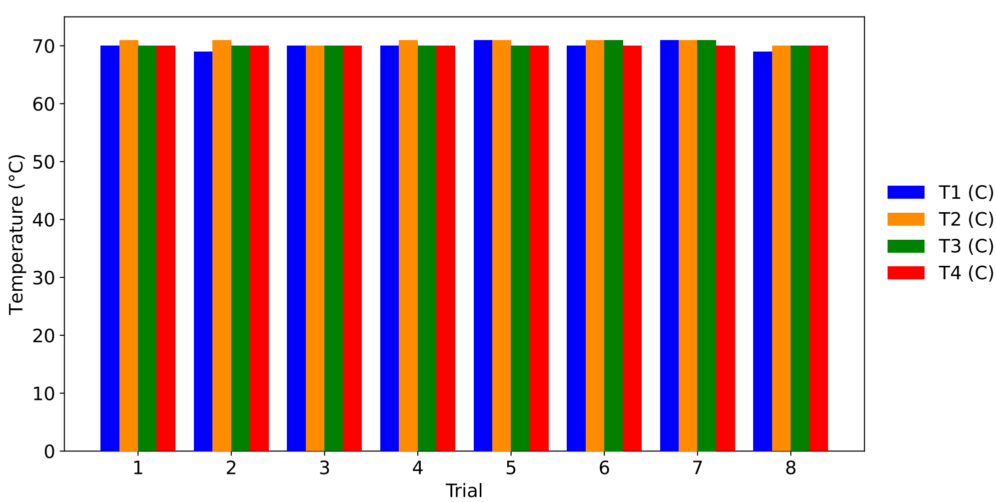

Fig. 8. The graphical result of dielectric temperature measurement

The recorded temperatures in the dielectric tests represent the thermal environment in which electron movement occurs within the dielectric materials. Temperature can significantly influence electron mobility and, consequently, the dielectric properties of a material [33]. Higher temperatures generally increase the kinetic energy of electrons, leading to more active electron movement. This can affect the dielectric constant and, in turn, the capacitance performance of the materials.

6. Discussion of the results of quality development framework building for bagasse leaf organic capacitor synthesis

The findings of this study address the critical issues regarding biomass-based capacitors, namely inconsistent precursor quality, sensitivity to pyrolysis conditions, and the absence of standardized synthesis protocols. Previous research on coconut shells, rice husks, and bagasse reported promising capacitance values but lacked reproducibility, with results often varying due to uncontrolled processing conditions [12–14]. In contrast, the application of the Taguchi method in this work provided a structured experimental design that systematically controlled synthesis factors, thereby reducing variability and enhancing comparability.

Compared with earlier bagasse carbon studies, which emphasized the benefits of pyrolysis and activation yet struggled with parameter sensitivity [15, 16], this work demonstrates that statistical optimization can yield stable capacitance values across trials. The narrow clustering of performance results around 0.9 nF confirms that process fluctuations exert minimal influence when parameters are optimized through Taguchi design. This marks a significant improvement over descriptive reports that did not employ robust statistical frameworks.

Furthermore, while prior studies incorporating lignin or biopolymers showed enhanced electrochemical performance [17], they offered little guidance on how to consistently replicate such improvements. By contrast, the present work identifies not only the optimal synthesis parameters but also the degree of influence each factor exerts, providing reproducible guidelines for future researchers. This level of standardization, which was absent in earlier literature on biomass-based capacitors, addresses the gap that organic material was directly used for energy purposes without prior optimization, such as found in [12–14], where optimization methods such as the Taguchi method were not applied.

Finally, the integration of morphological and chemical characterization into the Taguchi-based framework reinforces the method's robustness. SEM, FTIR, and GC-MS analyses confirmed that optimized conditions promote structural stability and functional group retention, which align with the observed electrical behavior. Thus, the Taguchi approach not only streamlines experimentation but also establishes a reproducible pathway for correlating synthesis parameters with material performance. This positions the method as a step forward toward international comparability in biomass capacitor development.

The application of the Taguchi method in this study has proven effective in optimizing the synthesis parameters for bagasse leaf-based organic capacitors. By utilizing an L8 orthogonal array design (Table 2), the experiment minimized the number of required trials from 64 to just 8 combinations, enabling a more efficient and resource-conscious process for parameter screening. Each factor and its level, such as capacitor width, bagasse leaf mass, and burner liquid type, was systematically varied to determine the most favorable combinations, ensuring a robust synthesis route for high-performance organic capacitors (Table 2). Using Minitab software, the L8 orthogonal array was generated, signal-to-noise (S/N) ratios were calculated under the "larger-the-better" criterion, and factor effects were analyzed through main effect plots and ANOVA. This statistical approach ensured that the influence of each parameter was quantified and ranked according to its contribution to capacitance stability.

The capacitance results across all trials (Fig. 2) demonstrated a narrow range of values, from 0.8897 nF to 0.9281 nF, indicating a high degree of stability and reproducibility in the fabricated devices. This clustering around the 0.9 nF mark reflects the ability of the Taguchi method to produce reliable outputs despite variations in process parameters. Similar findings have been reported in capacitor optimization studies where the Taguchi method improved consistency and reduced variability in dielectric responses [23]. The stable performance of the devices across different trials also implies that the bagasse-derived dielectric material is not highly sensitive to minor fluctuations in synthesis conditions a key trait for scalable production.

The chemical characterization via GC-MS (Fig. 3) and FTIR (Fig. 4) provides deeper insight into the organic matrix that supports the observed electrical performance. The GC-MS spectrum showed the presence of multiple dominant peaks, notably Peak 5 at 12.5 minutes with high intensity, indicating complex organic constituents likely formed during pyrolysis. This complex organic matrix contributes to the dielectric behavior through potential dipole interactions, supporting pseudocapacitance in the composite material [34].

The FTIR spectrum further confirmed the retention of oxygenated functional groups such as hydroxyl (O–H), carbonyl (C=O), and aliphatic C–H, as indicated by broad peaks at 3395 cm^{-1}, 1728 cm^{-1}, and around 2920–2853 cm^{-1}, respectively (Fig. 4). These groups are known to introduce dipolar polarization under an electric field, thus contributing to the overall capacitance performance [35]. Additionally, the presence of aromatic C=C and skeletal vibrations within the fingerprint region below 900 cm^{-1} confirms partial graphitization, enhancing both conductivity and dielectric polarization.

The morphological characteristics of both the SnO_2 particles (Fig. 5) and the bagasse leaf carbon–tin oxide composite (Fig. 6) corroborate the material's favorable electrochemical behavior. SEM images of the pure SnO_2 revealed a highly porous, agglomerated nanoparticle structure, with visible voids and interparticle channels that facilitate efficient ion transport and charge storage (Fig. 5, *a*, *b*). In the composite structure (Fig. 6, *a–c*), SnO_2 nanoparticles were well-dispersed across the carbon matrix, confirming successful integration. The hierarchical porous morphology, especially evident at 100,000× magnification, provides an interconnected pathway for charge carriers, enhancing both double-layer and pseudocapacitive effects in the organic capacitor [36].

Performance evaluation (Fig. 7) demonstrated the synergistic behavior of the composite material. The composite electrode exhibited the highest average voltage (1.1005 V), surpassing both pure carbon and pure SnO_2. This suggests improved electrochemical potential through the combination of conductive carbon and high surface area SnO_2. However, it also showed the lowest holding current (0.45 mA), indicating higher internal resistance or possibly slower ion mobility within the composite structure. This trade-off between voltage and current performance is typical in composite dielectric systems where material interactions introduce both benefits and constraints [37].

These findings highlight both the opportunities and unresolved challenges in utilizing bagasse-derived dielectrics. While our study demonstrates reproducible capacitance and structural stability, further questions remain regarding scalability, long-term cycling stability, and the influence of precursor variability across different bagasse sources. In particular, the absence of standardized optimization protocols means that results across studies are not directly comparable. By systematically applying the Taguchi method, this work provides a model for reducing trial-and-error experimentation and highlights the critical parameters that should be prioritized in future process designs. Thus, this study establishes a reproducible and efficient optimization framework for bagasse leaf-based capacitors logically follows from the identified gap in previous research.

Temperature measurements across the best-performing trials (Fig. 8) remained mostly stable, ranging from 69.01°C to 72.01°C. These fluctuations are minor and likely stem from slight differences in the dielectric material's composition and microstructure across trials. The effect of temperature on electron mobility is well-documented; higher temperatures increase kinetic energy and dipole alignment, potentially altering the dielectric constant and enhancing capacitance, while lower temperatures reduce these effects [38]. However, the relatively narrow range of fluctuation reinforces the robustness of the dielectric material synthesized via the Taguchi-optimized route.

The practical significance of our findings extends beyond laboratory demonstrations. In the IT sector, organic capacitors can be integrated into undoped organic metal-insulator-semiconductor (MIS) devices, where despite low charge concentrations, they exhibit capacitance-voltage characteristics comparable to traditional MIS capacitors. A physics-based model has already been validated through both TCAD simulations and experimental fabrication using poly(4-vinylphenol) and poly(3-hexylthiophene-2,5-diyl), highlighting their potential for application in future low-cost and flexible electronics [39]. In the energy domain, recent studies have demonstrated the feasibility of coupling organic capacitors with miniature wind turbines for energy harvesting. For instance, a 5-cm turbine operating between 2–8 m/s produced up to 0.2 W, with the generated energy effectively stored in an organic capacitor comprising Pd nanoparticles as charge-storage elements. This system outperformed commercial capacitors at low-frequency operation, proving the industrial potential of organic-based storage systems for sustainable energy harvesting and storage [40].

In addition to our own findings, a broader perspective can be drawn by comparing with other applications of the Taguchi method in advanced electronic systems. For instance, the study on optimizing the charge generation layer (CGL) in tandem OLEDs demonstrated that Taguchi's orthogonal arrays, when combined with nondestructive capacitance–voltage (C–V) measurements, successfully improved device efficiency from 3.56 cd/A to 6.13 cd/A [41]. Similar to our work, their results highlight the robustness of Taguchi-based optimization in handling multiple interacting parameters with limited experimental runs. While our study confirms stability of capacitance and efficiency improvements for organic capacitors, their OLED-focused work further validates the adaptability of Taguchi's method across diverse organic electronic platforms, proving that capacitance behavior under varying conditions can be reliably predicted and linked to performance metrics.

The partial carbonization observed in FTIR, along with the hierarchical porous structure seen in SEM, may also contribute to temperature resilience, as both factors influence heat dissipation and electrical stability. This supports the notion that structural and chemical tuning through optimization methods like Taguchi not only improves electrical output but also enhances thermal reliability.

Despite the promising outcomes, this study has several limitations that should be considered when applying the results in practice. First, the experiments were conducted under laboratory-scale conditions with controlled precursor sources, meaning that variability in bagasse leaf quality from different regions or sugar factories may affect reproducibility in real-world applications. Second, while the Taguchi method effectively reduced the number of trials and optimized synthesis parameters, it does not capture complex nonlinear interactions beyond the orthogonal array design, which could influence performance at industrial scale. Additionally, the electrochemical evaluation focused primarily on capacitance and short-term stability; long-term cycling performance and degradation behavior under operational stresses were not fully addressed.

The main shortcomings of the study include the narrow capacitance range of the fabricated devices, which, although stable, remains relatively low compared to state-of-the-art supercapacitors. Furthermore, the scope of morphological and chemical characterization was limited, leaving other advanced techniques such as X-ray photoelectron spectroscopy (XPS) or Raman spectroscopy unexplored, which could provide deeper insights into surface chemistry and defect states.

Future development of this research may involve extending the optimization framework to other agricultural wastes to test its generalizability, scaling up the synthesis to pilot-plant level, and incorporating advanced electrode modifications such as heteroatom doping or hybrid composites to boost energy density. Long-term cycling stability tests, coupled with in situ monitoring of structural and chemical changes, will also be essential to validate the durability of bagasse leaf-based capacitors. Finally, integrating this framework with machine-learning-based predictive models could further accelerate parameter optimization and broaden the applicability of sustainable organic capacitors in energy storage and flexible electronics.

7. Conclusions

1. The Taguchi method proved effective for systematic optimization, reducing the experimental workload from 64 to 8 trials through the L8 orthogonal array while still enabling efficient evaluation of four critical parameters capacitor width, bagasse leaf mass, burner liquid volume, and burner liquid type.

2. Optimized conditions yielded capacitance values consistently within a narrow range of 0.8897–0.9281 nF, with less than 5% variation across replicates. This validates the reproducibility of the fabrication process and shows that

parameter optimization contributed directly to stable device performance.

3. Characterization confirmed the material's appropriateness for dielectric applications: SEM revealed uniform porous morphology, FTIR detected functional groups including hydroxyl and carboxyl, and GC-MS identified organic compounds associated with electroactive behavior. These results support the electrochemical potential of bagasse-derived carbon as a capacitor dielectric.

4. The fabricated capacitors achieved measurable and stable capacitance under optimized conditions, showing significant improvement compared to non-optimized samples. The use of bagasse leaf waste as a precursor demonstrates both technical viability and environmental sustainability, underscoring its potential application in green electronics and eco-friendly energy storage devices.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this sudy, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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