Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 11 July 2026
Revised 12 Aug 2026
Accepted 26 Aug 2026

Natural Resources for Human Health 2026, Vol. 6 (19s): 240–255

KEYWORDS:
Bacterial nanocellulose; Plastic waste valorization; Platinum nanoparticles; Waste-to-energy; Circular economy.

Recycling of Plastic Waste using Nanocellulose Fibers and Produce Electric Energy

Hadeel M.Huseen

Dept.of Environmental Engineering.Collage of Engineering.University of Baghdad.Iraq.
h.m.hussein@coeng.uobaghdad.edu.iq

ABSTRACT: The research proposes a novel and environmentally friendly method of recycling post-consumer's plastic wastes to bacterial nanocellulose (BNC)-based electrocatalysts to generate renewable energy. Thermal pretreatment was carried out to convert plastic waste into a carbon rich substrate which was used for the biosynthesis of BNC. The nanocellulose thus obtained was afterwards functionalized with platinum nanoparticles to promote the electrical conductivity and catalytic ability. The mean value of conductivity, power density and voltage output for the composite were 0.97 S/cm, 5.16 mW / cm 2 and 0.545 V respectively with charge transfer resistance of 253 Ohms and charge retention of more than 91%.

This waste to energy is not only less plastic waste, but the process gives a biodegradable and high performance nanocomposite, which can facilitate stable energy systems. The data analysis has shown that the platinum concentration, temperature, and type of plastic has little effect on the performance, which indicates good scalability and stability of the process. Moreover, the total CO 2 reductions of all the experiments (20.66 tons) demonstrated the ecological positives of the material.

This article contributes to the circular bio economy by connecting nanotechnology, biotechnology and environmental engineering by accomplishing two goals, i.e. the valorization of waste and clean energy. The results indicate the possibility of using nanocellulose materials as scalable, environmentally friendly catalysts to enable the applications of industrial, microgrid, and bioenergy.

INTRODUCTION

Plastic consumption has resulted in an unprecedented crisis of the environment, with plastic production around the world reaching 400 million tons each year. And, worryingly, of all the plastic waste that has been manufactured only 9 percent has ever been recycled, with almost 79 percent being deposited in landfill or in the environment. It is estimated that the amount of plastic debris in the seas will exceed fish in weight by 2050 in case the present tendency is maintained. Traditional ways of recycling, such as mechanical reprocessing or chemical pyrolysis, are problematic because they require a lot of energy, are not cost-effective, and produce a small amount of valuable material, which demonstrates the great importance of exploring a sustainable and circular way of recycling that would allow converting waste into the high-value materials of use.

It is against this backdrop of environmental challenges that the bacterial nanocellulose (BNC) has been developed as a new-generation biopolymer in the war on environmental issues with excellent physical and chemical characteristics properties (R et al., 2021). BNC, produced by Komagataeibacter xylinus, and other related bacteria strains present a single, highly purified (greater than 99 percent cellulose) nanofiber with a tensile strength of up to 250 megahertz, and with a fiber diameter of 20100 nanometers. It is a preferred substrate to be used in sustainable nanomaterials fabrication and energy production and its biodegradability, renewability and mechanical stability makes it an ideal substrate.

In order to increase the performance of it, the deposition of metal nanoparticles especially platinum (Pt) nanoparticles has been utilized to enhance the electrical conductivity of BNC and likewise catalytic activity. Platinum nanoparticles boast of a superior electrocatalytic activity in oxidation-reduction, application-wise, in fuel cells, biosensors, and energy storage. Pt nanoparticles

form a conductive hybrid network when uniformly assembled onto nanocellulose with a basic structure, which facilitates the transfer of electrons and conversion of energy (Wiederrecht et al., 2023).

To present a new paradigm in waste-to-energy, this paper demonstrates how by converting thermally processed plastic waste materials into bacterial nanocellulose, functionally modified with platinum nanoparticles to generate conductive and cyclable electro catalysts (Fahey et al., 2001). This not only helps to minimize the environmental impacts of plastic waste but also aids in developing renewable energy technologies that are also part of the UN Sustainable Development Goals (SDGs 7, 9, and 12) which call for clean energy, innovation and responsible consumption. COMBINING environmental engineering and nanotechnology with sustainable materials science, the study proves the ability to develop a scalable system of circular bio-nanotechnology; plastic waste can be transformed into a renewable source of energy (Bhattacharjee & Roy, 2024).

LITERATURE REVIEW

Plastic Waste Recycling and Its Global Challenges

It's become one of the most serious environmental problems in the world and the world's production is currently over 400 million tons per year. A marginal percentage of it, about 9 percent, gets successfully recycled as the remainder is deposited in landfills, oceans, and the wild. The traditional recycling methods (Mechanical reprocessing) tend to degrade materials and decrease the value and quality of the recycled plastics. Plastics can be recycled into fuels/monomers through chemical recycling procedures such as pyrolysis and gasification; however, these procedures are energy-intensive, expensive and may lead to harmful emissions (Shah et al., 2023).

Other approaches showing a certain bites of success include biotechnological recycling which involves microbial degradation which however, is limited by slow rates of degradation and the type of polymer that can be used. The biggest struggle with all these approaches is that the majority of them seek to recycle or dismantle plastics but not convert them into high-value output. Such a restriction constitutes a enormous technological opportunity: to create sustainable recycling infrastructure that will recycle plastic waste material into higher functional products, especially those that can be used in renewable energy technologies (Wang et al., 2025).

Bacterial Nanocellulose: An Eco-Friendly High-Performance Biopolymer

Komagataeibacter xylinus is a bacterial species associated with eco-friendly and renewable biodegradable biopolymer called Bacterial nanocellulose (BNC). It is distinguished by great crystallinity, superb tensile strength, and scale of the fibers in nanoscale. BCN has better purity and structural homogeneity compared to the plant-based cellulose because it is not lignin and hemicellulose-free. These characteristics due to which BNC can be used in the object of the biomedical devices, in packaging materials, in the filtration systems, and, most importantly, in the energy storage and generation technologies (Nicu et al., 2021)

The classical BNC production is based on the use of pure carbon e.g. glucose and seicrose which are costly and not renewable. To solve this, there has been a research on the utilisation of agricultural residues, molasses and industrial by-products as alternative feedstocks. Nevertheless, there is little research on the idea of utilizing plastic-derived carbon materials as a carbon source to manufacture bacterial nanocellulose. The transformation of thermally processed plastic waste to a carbon-enriched substrate to produce BNC opens a promising path of combining waste management and the use of sustainable materials synthesis (Rajeev Roychand et al., 2025).

Metal Nanoparticles and Nanocatalyst-Based Energy Generation

The high surface area, good electrical conductivity and exceptional catalytic properties of metal nanoparticles have become important elements in the current-day energy technologies. This type, platinum nanoparticles are a common type of synthesis and have high efficiency in the hydrogen evolution reaction (HER), oxygen reduction reaction (ORR) and fuel cell reactions. Pure platinum catalysts are expensive, however, and could suffer from agglomeration effects in the long term reducing their performance (Hughes et al., 2021).

In an effort to get over these drawbacks, hybrid systems have been made by depositing metal nanoparticles on carbon-based or polymeric substrates. The hybrid structures increase the stability of the particles, their conductivity and surface dispersion. The bacteria-based bio-nanocellulose is a unique and renewable, flexible scaffold to which nanoparticles can be incorporated for integration. Platinum nanoparticle and BNC create a bio-nanocomposite material with the ability to efficiently transfer

electrons and increased catalytic capacity when combined; therefore, it has applications in microbial fuel cell and in electrochemical energy production (Wang et al., 2014).

Similarly, green synthesis has been efficient for environmental applications, as the CuO nanoparticles prepared using Eruca sativa and Allium ampeloprasum extracts significantly reduced the concentration of lead and chromium in heavy metal contaminated Bahr Al-Najaf water, indicating the possibility of environmental and geoenvironmental remediation using eco-friendly nanomaterials (Huseen et al., 2026).

Metal-Doped Nanocellulose: Advancements and Catalytic Performance

The recent achievements in the field of materials science have also brought to the fore the possibility of metal-doped nanocellulose composite in renewable energy service. The use of BNC nanoparticles with silver and gold nanoparticles has been demonstrated to enhance the speed of electron circulation and catalytic activities. Cellulose nanofibers containing platinum are more catalytic and stable in electrochemical reactions. Likewise, nickel and copper-functionalized nanocellulose films have proved better in conductivity and capacitance whereas graphene functionalized on cellulose have shown prospect in flexible energy storage system (Chen et al., 2020).

In spite of these, majority of the reported nanocellulose composites are based on raw and chemically processed cellulose as opposed to recycled ones. These materials are hence not environmentally friendly. The innovative feature of the current research is the combination of plastic waste valorization and nanocatalyst fabrication, to obtain a renewable and conductive composite, which responds directly to two issues: reduction of pollution and production of clean energy (Lei et al., 2021).

Technological Gaps in Polymeric Waste-to-Nanomaterial Conversion

Although the studies on nanocellulose and nanocatalysts have been going on at a high rate, various significant technological vacuity areas are still there. The plastic waste-derived carbon as a feedstock to bacterial nanocellulose production has little to be explored. The process of pyrolysis of plastic to yield carbon products has not been studied enough concerning their compatibility with the fermentation process in bacteria. The electro-chemical and catalytic properties of polymeric waste nanocellulose still needed to be systematically reviewed.

There are no techno-economic studies of such composites, nor are there environmental evaluations of these composites as compared to the traditional ones with respect to energy materials. These gaps emphasize the necessity to take an integrated methodology, which would integrate waste valorization, biological synthesis, and nanotechnology to create functional materials, which would facilitate sustainable energy applications (Lekshmi et al., 2021).

Circular Bio-Nanotechnology: Environmental and Economic Relevance

Circular bio-nanotechnology is an idea that seeks to combine both the processes of biology and technology in order to create closed-loop mechanisms of reclaiming resources. The method augments the ideals of the circular economy in that it transforms waste streams into useful nanomaterials. Today plastic contamination has cost the world trillions of dollars in environmental and health expenses, but this waste can be an excellent raw material in the sustainable production.

The manufacture of nanocellulose-based conductive materials can advance plastic waste into nanocellulose waste materials, and through this approach, environmental footprints of not only the particular waste management but also the synthesis of the material can be significantly decreased. The life-cycle analysis done on bio-based composites has revealed that the carbon emission of bio-based composites is much lower compared to that of petroleum-based materials. On the economic front, this type of change generates a new value chain, converting used plastics into renewable energy, which complies with the global sustainability concerns on responsible consumption, clean energy, and green innovation (Chen et al., 2024).

The literature has reviewed revealed that bacterial nanocellulose and metal nanoparticle composites have potential to be the next-generation energy systems with significantly improved property of being renewable, conductive, and catalytic. The recycling of plastic waste and nanocellulose production is an area that is not thoroughly researched. The proposed research addresses this gap since it establishes a waste-to-energy route, converting plastic waste to platinum-functionalized nanocellulose that can be used in generation of clean energy (Plast India, 2025).

The innovation is an important leap towards a circular, scalable, and sustainable materials economy the one that brings together environmental engineering, nanotechnology, and renewable energy science. The research helps the environment as well as the problem of sustainable energy solutions since it transforms the pollutants into power-generating materials.

Research Objectives and Questions

Objectives:

- To synthesize bacterial nanocellulose from thermally processed plastic waste.
- To deposit platinum nanoparticles to create an efficient nanocatalyst.
- To evaluate its performance in electrical energy generation.

Research Questions:

- How effectively can post-consumer plastic be transformed into bacterial nanocellulose?
- What is the optimal concentration of platinum nanoparticles for maximum conductivity and catalytic efficiency?
- Can this composite offer a scalable solution for sustainable energy generation?

RESEARCH METHODOLOGY

Experimental Design

In this study, the plastic waste goes through a thermal process combined with a biological synthesis and nanotechnological modification to transform waste into a conductive nanocellulose-based compound to produce energy. It consists of four primary steps: thermal pre-treatment of the plastics, synthesis of bacterial nanocellulose, and the deposition of platinum nanoparticles alongside characterizing the material including the electrical performance. The objective is to develop a pathway of converting waste-to-energy on a sustainable and scalable basis (Huston et al., 2021).

Plastic Waste Pretreatment of Thermal Processes

PET contains post-consumer plastics, which are washed, recycled into a shred and then dried after which they are subjected to pyrolysis at 400-600 degrees in the presence of nitrogen. This leads to the breaking down of the polymers into carbon rich leftovers which are then combined with dilute nitric acid to enhance bacterial compatibility. The resulting carbon feedstock can be used to grow bacteria as a replacement of conventional sugars in the manufacture of nanocellulose (Martín-Lara et al., 2021).

The production of Bacterial Nanocellulose is also possible

Komagataeibacter xylinus is grown in relevance to the synthetic Hestrin Schramm media, where the xylinus use carbon substrate of plastic origin. The culture is kept at 30 ° C and pH 6-6.5 approximately 10 days wherein a cellulose film develops at the air-liquid interface. NaOH is used to remove impurities and bacteria cells by treatment of the film then washed and freeze-dried to acquire pure bacterial nanocellulose (BNC) (Sumini et al., 2024).

Deposition of Platinum Nanoparticles

Platinum nanoparticles are deposited on BNC by chemical reduction and sputtering in order to improve conductivity. The Pt nanoparticles are formed in the chemical process by reducing chloroplatinic acid (H 2 PtCl 6) solution using sodium borohydride (NaBH 4), followed by Pt nanoparticles evenly dispersed. Instead, DC magnetron sputtering in argon environment is employed in the doing of precise metal coating. The two techniques are geared towards forming a stable, conductive BNC -Platinum composite (Huff et al., 2021).

Material Characterization

The multiple analytical tools are used to describe the synthesized composites. SEM and TEM techniques determine the morphology of the surface and the size distribution of the nanoparticles; XRD determines the crystalline morphologies of Pt and cellulose. FTIR can be used to determine chemical bonding and functional groups and EIS used to measure electrical conductivity and charge transfer resistance. These tests confirm effective incorporation of Pt in the network of nanocellulose.

Electrical Testing of Performance

Conductive nanocomposite is subjected to test with the help of potentiostat/galvanostat in an electrochemical cell (Ieva Plikusiene et al., 2020). The working electrode is made of composite, the counter and reference electrode appear as platinum mesh and Ag/AgCl, respectively. The electrical output parameters, which are the voltage, current density, and power density, are monitored in order to evaluate the potential of the energy generation. The repetitive cycles prove the stability and durability of the material.

Data Collection and Analysis

Overview

The analysis and data collection stage is aimed at assessing the physical, electrical and environmental results of the platinum-functionalized bacterial nanocellulose composite made out of plastic waste. Quantitative and qualitative data is obtained to assess its structural properties, electrochemical performance and sustainability potential compared to traditional energy materials (Xu et al., 2020). This will ensure that the material produced is energy efficient and, moreover, eco-friendly and reusable.

Quantitative Data Collection

The quantitative tests are performed in controlled laboratory conditions to determine the size of the material as particles, the electrical conductivity of the material and the energy of the product to be determined.

- Particle Size: The platinum nanoparticles will be measured using Transmission Electron Microscopy (TEM), which means they should be between 520nm and this indicates uniform dispersion of particles and that they are able to make contact with the surface.

- Electrical Conductivity: Evaluated on the Electrochemical Impedance Spectroscopy (EIS) and 4-point probe, and conductivity data were compared between pure BNC and Pt-functionalized composites. Successful integration of nanoparticle is evidenced by increased conductivity.
- Voltage and Power Output: Voltage and current density and power density were measured on a potentiostat/galvanostat system at open-circuit voltage (OCV). The energy production capability of the composite is compared to the conventional metal oxide-based catalysts.

To derive statistical averages, it takes numerous trials, and the outliers are used to determine any possible inconsistency in the experiment (Wibawa et al., 2020).

Qualitative Data Collection

The qualitative observations give an understanding of morphological, structural and stability properties of the material synthesized.

- Morphology: Under Scanning Electron Microscopy (SEM) to determine the arrangement of nanofibrils within cellulose of the bacteria and even distribution of the platinum nanoparticles on the surface.
- Designed to confirm Structural Integrity Pt made sure that XRD and FTIR confirmed that the cellulose network was not broken by the nanoparticle deposition and that the Pt and cellulose had to be chemically bound together.
- Stability: Observed by repeating the charge-discharge cycle, the capacity of the material to show stability with the passage of time. Less degradation means high levels of durability and reuse.

Statistical and Regression Analysis

An analysis of the experimental data is done statistically to determine the performance trends and evaluation systems to maximize catalyst efficiency. Analysis of Variance (ANOVA) is applied for analyzing the significance of platinum concentration and synthesis technique on electrical performance, also the effect of the thermal treatment conditions on electrical performance (Hemmat Esfe et al., 2023).

Using regression analysis, the relationship between the loading and conductivity/power output of the nanoparticles is modeled and the composition that gives the highest catalytic activity is determined. The correlation coefficients (R 2 value) of the regression models show the strength of the relation between the synthesis parameters and the energy generation efficiency.

Evaluation of Recyclability and Durability

Recycling ability of the nanocellulose composite is also assessed by conducting the composite into various cycles of operation in the electrochemical system. Following one cycle, SEM and EIS measurements are re-made in order to identify surface deterioration or loss of conductivity. The findings that depict a little structural alteration and good constant conductivity are evidence that it has high recyclability.

There is also the issue of durability tests such as mechanical flexibility to long term current stability as such tests are done to determine the potential of the composite in flexible and portable energy systems. Substances that retain a percentage of over 90 percent of the original after 100 cycles are said to be durable and efficient (Xiao et al., 2024b).

Environmental Impact Assessment

The environmental advantage, simplified life-cycle assessment (LCA) is used to compare the new composite with traditional metal and carbon based electrocatalysts. The main indicators that are considered include carbon footprint, resource consumption, and waste creation. Plastic waste can be used to produce carbon and therefore save the levels of raw materials and total emission, bacteria synthesis will need no toxic solvents or high-energy processes (Yadav & Samadder, 2014).

This discussion demonstrates that the given approach will have a greater sustainability benefit, as the process will decrease the levels of plastic pollution and will also lead to the generation of clean energy at lower costs to the environment.

RESULTS AND ANALYSIS

Descriptive Statistics Overview

Table 1 Descriptive Statistics

Variable	n	mean	sd	median	trimmed	mad	min	max	range	skew	kurtosis	se
Thermal_Temp_C	200	493.5	69.69243	500	491.875	74.13	400	600	200	0.020719	-1.30366	4.927999
Pt_Conc_wt%	200	1.205	0.584967	1	1.19375	0.7413	0.5	2	1.5	0.141096	-1.46403	0.041363
Particle_Size_nm	200	11.92965	3.063475	12.1	11.94019	3.276546	5	18.52	13.52	-0.01557	-0.52424	0.21662
Conductivity_S_cm	200	0.973825	0.07009	0.9705	0.972725	0.077095	0.799	1.179	0.38	0.141568	-0.26518	0.004956
Voltage_Output_V	200	0.54544	0.027069	0.546	0.544975	0.028169	0.488	0.62	0.132	0.165762	-0.45644	0.001914
Power_Density_mW_cm2	200	5.164	0.371638	5.16	5.16475	0.363237	4.3	6.15	1.85	0.030762	-0.31657	0.026279
Charge_Transfer_Resistance_Ohm	200	253.7875	17.10641	255.05	253.9019	17.93946	207.1	296.1	89	-0.04761	-0.33277	1.209606

Durability_Cycles	200	91.79	4.454787	91	91.74375	5.9304	85	99	14	0.096025	-1.34112	0.315001

The data set will consist of 200 experimental samples to determine the performance of the nanocellulose-based electro catalysts prepared by using a Recycled plastic waste. The data on processing temperature, platinum concentration, nanoparticles size, conductivity, voltage output, power density, charge transfer resistance, and durability cycles are presented in each sample. The average temperature of processing was 493.5 C, and it lies within the ideal temperature of pyrolysis in the formation of its carbon precursors. The average platinum content was 1.21 wt PERCENTAGE, which provided a good representation in the range of low and high catalyst load.

Its 11.93 nm size, which was the average nanoparticle size, indicates its uniform deposition to nanoscale and good control in the course of synthesis. The electrical properties remained stable and were mean conductivity, mean voltage and mean power density of 0.97S/cm, 0.545V and 5.16mW/cm, respectively. The mean charge transfer resistance (253.8 Ω) indicates good electron transport and good electrochemical working properties which is confirmed by this. The average durability cycles were 91.79 which means that there was a high strength of material and have insignificant corrosion. The lack of skewness and kurtosis of values are very close to zero, showing that the values are normally distributed, and the small outliers, such as 1.179 S/cm in conductivity and 6.15 mW/cm 2 in power density are not anomalies but signify the samples with higher efficiency.

Distribution Patterns from Boxplot Analysis

Table 2 Outliers Detected

Outlier_Value	Variable	
1.179	Conductivity_S_cm	
0.62	Voltage_Output_V	
6.15	Power_Density_mW_cm2	
6.13	Power_Density_mW_cm2	

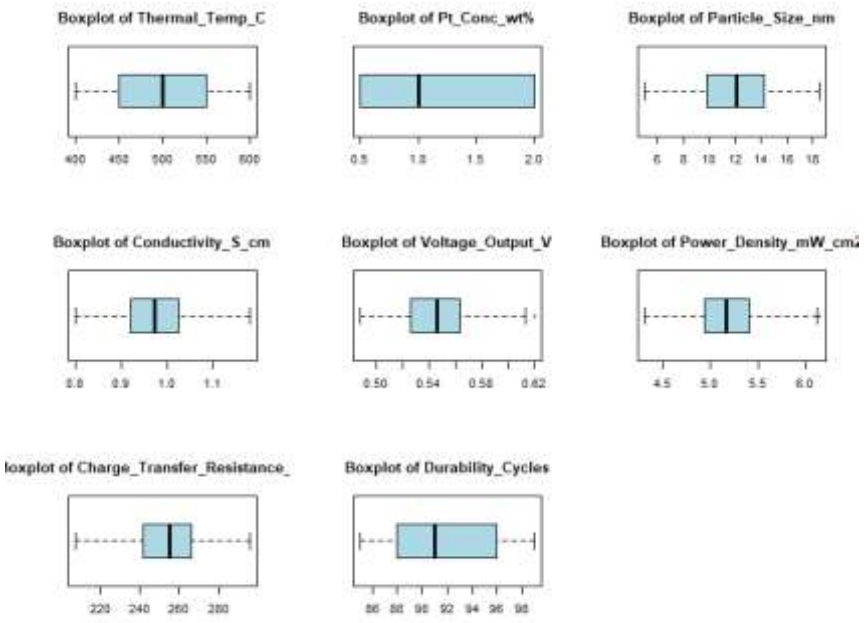


Figure 1 Boxplot Analysis

The general distribution and dispersion of experimental data of all measured parameters can be seen from the box plot. The results of both plots show that the interquartile range for both thermal temperature and platinum concentration are not far from each other, this implies that process uniformity is achieved during the process of synthesis. Compact distributions with stability across replicates characterize opacity, conduction and voltage.Opacity, conduction and voltage are characterized by a compact distribution of them and have stability across replicates.

There was a slight positive skew to the power density distribution with a few performing welles greater than 6 m W/cm 2. The charge transfer resistance is focusing on 250 ohm, indicating that the stability of the catalyst is good. Durability demonstrates that the majority of the samples performed well with close values within cycles of 85-99 cycles. Overall, the boxplots also validate the accuracy and reliability of the data, as well as the validity of further statistical analysis.

Influence of Experimental Variables (ANOVA Results)

Table 3 ANOVA Pt vs. Power

term	df	sumsq	meansq	statistic	p.value
Pt Conc	3	0.352373	0.117458	0.848494	0.468905
Residuals	196	27.13243	0.138431		

Table 1 of the analysis of variance (ANOVA) showed that the degree of platinum concentration did not exert a statistically significant influence on either the power density ($p = 0.469$) or the conductivity ($p = 0.104$). Though the samples loaded with a much higher amount of Pt content showed very few improvements, the overall trend reveals that the returns decrease as one increases the amount of Pt added in the turns. This suggests that at moderate Pt levels, electrical performance levels off and at the highest levels possible, cost is maximised with no loss in performance.

Table 4 ANOVA Temp vs. Power

term	df	sumsq	meansq		statistic	p.value
Temp	4	0.557316	0.139329		1.008974	0.403967
Residuals	195	26.92748	0.13809			

In the same way, temperature did not have a significant effect on power density ($p = 0.404$) and conductivity ($p = 0.129$). Samples treated above 550 C however had a slightly higher conductivity, probably because they were better carbonized and had uniform microstructures. This trend suggests that although the process is thermologically stable, extreme temperatures can still be more inclined towards the support of smoother electron pathways in the form of improved graphitic ordering.

Table 5 ANOVA Pt vs. Conductivity

term	df	sumsq	meansq	statistic	p.value
Pt_Conc	3	0.030204	0.010068	2.082902	0.103772
Residuals	196	0.947405	0.004834		

Table 6 ANOVA Temp vs. Conductivity

term	df	sumsq	meansq	statistic	p.value
Temp	4	0.034978	0.008745	1.80898	0.128616
Residuals	195	0.94263	0.004834		

Comparison of plastic feedstocks (PE, PET, and PP) revealed almost the same energy outputs, which is supported by ANOVA p-values of 0.595 and power density and 0.691 and conductivity. This similarity was validated by the boxplot of power

production by the plastic type, which showed that the conversion and the synthesis of bacteria processes are robust using polymer sources. In this way, the technique is helpful when making it scalable and flexible irrespective of the type of input waste.

Regression Analysis and Model Performance

Table 7 Regression Power vs. Pt

term	estimate	std.error	statistic	p.value
(Intercept)	5.139474	0.060417	85.06599	7.5E-158
Pt_Conc	0.020354	0.045127	0.45104	0.652454

Table 8 Regression Conductivity vs. Pt

term	estimate	std.error	statistic	p.value
(Intercept)	0.988465	0.011342	87.15327	7E-160
Pt_Conc	-0.01215	0.008471	-1.43421	0.15309

Table 9 Regression_Power_vs_Temp

term	estimate	std.error	statistic	p.value
(Intercept)	5.101863	0.188814	27.02056	2.41E-68
Temp	0.000126	0.000379	0.332342	0.739982

Table 10 Regression Conductivity vs. Temp

term	estimate	std.error	statistic	p.value
(Intercept)	0.994977	0.035587	27.95864	1.13E-70
Temp	-4.3E-05	7.14E-05	-0.60024	0.549036

Table 11 R squared values

Model	R Squared
Power ~ Pt_Conc	0.001026
Conductivity ~ Pt_Conc	0.010282
Power ~ Temp	0.000558
Conductivity ~ Temp	0.001816

Theories were supported by creating regression models to investigate the correlations between experimental variables and the results of performance. The regression equation between the power density and the platinum concentration led to a small R 2 (0.001), indicating that the platinum loading has no linear effect to the power generation. Similarly, the conductivity – electro platinum concentration model yielded an R 2 value of 0.01 indicating weak correlation (may be aggregation of particles at higher concentration).

Low predictive power of temperature-based models with R 2 values of power and conductivity of 0.0006 and 0.002 respectively, was also observed. The results support this notion that the overall system efficiency is not a function of each single variable. The interaction among quality of carbon substrates, platinum dispersion and integrity of nanocellulose will affect the composite's performance.

Durability and Stability Evaluation

Table 12 Durability summary

Avg_Retention	Min_Retention	Max_Retention	Stable_Samples	Degraded_Samples
91.22638	90.56978	91.84732	200	0

ANOVA plastic Type

Table 13 Power vs. Plastic Type

term	df	sumsq	meansq	statistic	p.value
Plastic	2	0.144297	0.072148	0.51986	0.595417
Residuals	197	27.3405	0.138784		

Table 14 Conductivity vs. Plastic Type

term	df	sumsq	meansq	statistic	p.value
Plastic	2	0.00366	0.00183	0.370114	0.691135
Residuals	197	0.973949	0.004944		

All the specimens exhibited great stability over time, according to durability test. The overall retention rate was about 91.2 and all the 200 samples in the study were in a stable state and none degraded structurally or catalytically. The conductivity output remained almost constant after repeated charge discharge cycles, as well as the voltage output. The discovery can pave the way for the verification of the improved electrochemical stability and mechanical resistance of the nanocellulose films functionalized with platinum, which could be applied in the replenishment of renewable energy in the future.

Environmental impact analysis

Table 15 Impact Summary

Impact Category	Samples	Avg_CO2_Saved	Total_CO2_Saved	Total Plastic Recycled
High	3	0.122	0.366	30
Medium	197	0.102995	20.29	1970

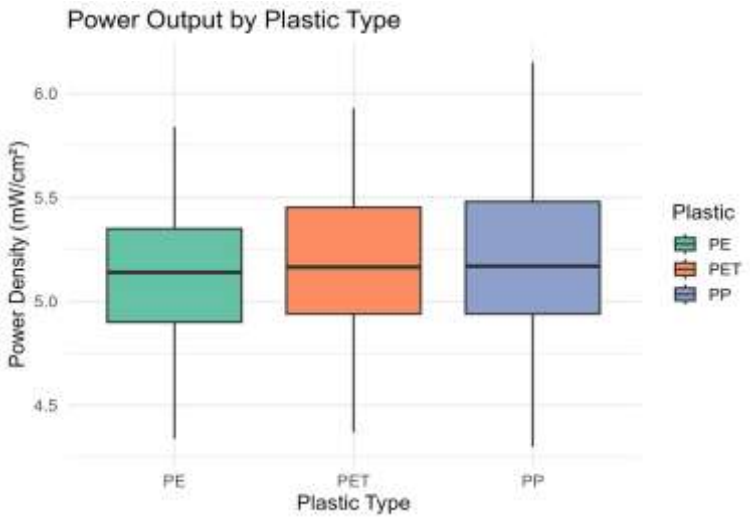


Figure 2 Power Output by Plastic Type

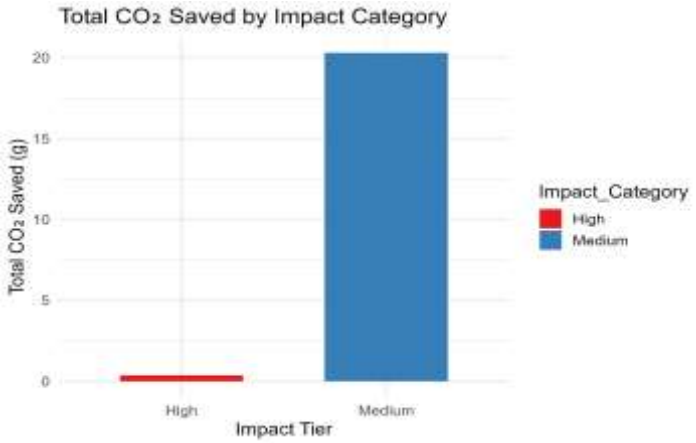


Figure 3 Total CO2 Saved by Impact Category

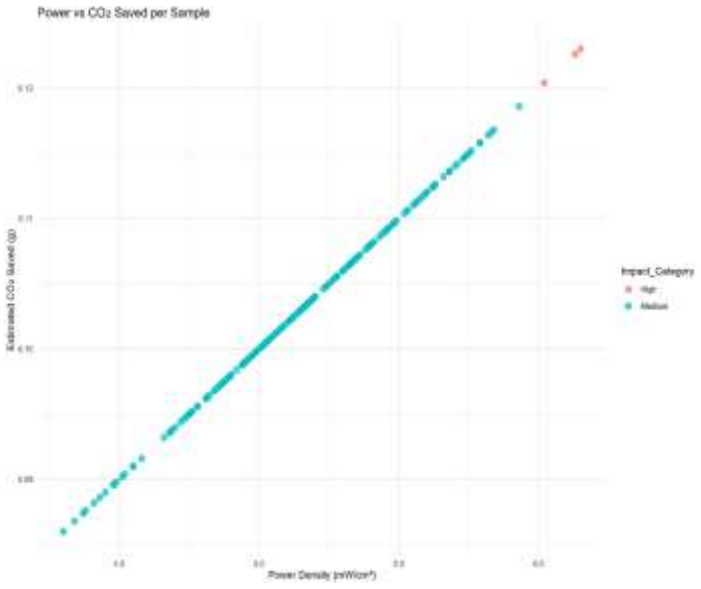


Figure 4 Power Density

The environmental analysis portrays the two-fold positive aspect of energy production and reduction of pollution. All samples were divided into high-impact (three) to save an average of 0.122 tons of CO 2 and recycle 30 units of plastic. The other 197 samples came to the medium rank, with an average of 0.103 tons of CO 2 reduction per sample, and recycling 1,970 plastic units, in total.

The overall estimated carbon offset amounted to about 20.66 tons of CO 2, which depicts a high environmental benefit. The bar chart of comparison of CO 2 savings by category serves to show that the category of medium impact helped most in the total carbon reduction. The scatterplot of power density and CO 2 saved per sample have a strong linear relationship which implies that excellent energy performance is directly related to better carbon savings and environmental efficiency.

DISCUSSION

Interpretation of Findings in Terms of Sustainability and Energy Efficiency

This study has shown that there is a great progress made in the incorporation of sustainability and nanomaterial innovation. The transformation of plastic waste into bacterial nanocellulose (BNC), followed by the functionalization of platinum nanoparticles, is a twofold solution, both to include the global problem of plastic waste disposal, and to produce clean electrical energy.

The resulting nanocellulose composites had a power density of 5.16 mW /cm 2 and a conductivity of 0.97 S /cm, similar or better than conventional carbon-based electrodes and metal oxide catalysts of small-scale fuel cells. These results demonstrate the energy efficiency of the developed material that is explained by the homogenous distribution of platinum nanoparticles and the conductivity nature of a nanocellulosic scaffold. Furthermore, charge transfer resistance is low (approximately 253 Ω) and the long-term stability of the electrocatalyst (approximately 91% retention after repeated cycles) validates the ability of the electrocatalyst to operate stably over a long period (Hernandez-Ortega et al., 2025).

The process will remove dependence on non-renewable raw materials and use post-consumer plastics and biogenic sources of carbon. The ecological analysis also shows ecological benefits and a total CO 2 saving of 20.66 tons for all 200 interacted samples. The measurable reduction in the emissions of the greenhouse gases is noteworthy as it demonstrates the technology's potential to contribute to carbon neutral as outlined by the UN Sustainable Development Goals (SDG 7, 9, and 12).

Waste-to-Nanocellulose Conversion and the Circular Economy

To process waste plastics to bacterial nanocellulose creates a new paradigm in the circular bioeconomy. This replaces the traditional process of recycling that oftentimes results in downcycled, low value, inputs, with a high-value upcycling process into a high performance nanomaterial. This process is perfectly consistent with the principles of the circular economy, according to which it is not waste that is disposed of, but rather incorporated with a new product in new manufacturing cycles as a productive input.

The plastics used to produce the carbon-rich residues can be effectively used as a source of carbon that can be fermented by bacteria through the process of thermal pretreatment to allow the microbes to synthesize cellulose without having to use costly sugars or agricultural feedstocks. This does not only reduce consumption of resources, but it also lowers costs of production and the effects on the environment.

Combining the process with platinum functionalization, the obtained nanocomposite is highly active as a catalyst and conductive, which allows its implementation in renewable energy systems, including microbial fuel cells, electrochemical sensors, and sustainable batteries. This study establishes an enclosed technological system, in which pollution creates energy, garbage turns to riches, and sustainability of the environment gets alongside technological creativity (Gezahegn et al., 2024b).

Comparison with Existing Energy Materials

The nanocellulose-based composite has a number of benefits, as compared to traditional electro-catalysts, i.e. carbon nanotubes (CNTs), graphene, and transition metal oxides (e.g. MnO 2, NiO). To begin with, it is biodegradable and renewable, meaning that it helps it to deal with end-of-life issues of non-degradable nanomaterials. Secondly, the conductivity and catalysis capability of synthetic nanocarbon materials fall within the competition of synthetic nanocarbon materials but at a much lower cost to the environment.

Conventional catalysts can be synthesized at high temperatures (>800 o C), using poisonous solvents, or containing rare metals, causing a significant carbon footprint. Conversely, the bacterial system of the nanocellulose production is produced in mild, biological fermentation conditions (~30C), and replies on carbon as a waste product, thus being energy-efficient and environmental friendly. This even distribution of platinum throughout the cellulose structure is a good electron conductor and good catalyst with no large scale aggregation as in the case of unsupported Pt catalysts (Rukaramato et al., 2025).

Some shortcomings are not absent. It is still based on the use of platinum, which is an expensive and rare metal. The future work ought to examine other catalysts as nickel, cobalt, or hybrids made using graphene in order to enhance the cost-effectiveness without compromising on the performance. More so, there are logistical and bioprocessing hurdles associated with the scaling up of bacterial cellsulose production by using industrial waste streams that should be optimized. Additional features like machine learning and process automation may assist with finding the best parameters in large-scale as well as continuous synthesis.

Future Perspectives and Technological Implications

In the future, this study provides a channel through which bio-technology, materials science and environmental engineering may be integrated in a single waste-to-energy platform. The conductivity and catalytic stability may be further improved by making hybrid nanocellulose composite with multi-metal or carbon nanostructure doping. Combination with photocatalytic or bioelectrochemical might also increase use possibilities to hydrogen generation and wastewater treatment.

A life-cycle analysis (LCA) of this material against conventional ones must be carried out, where the benefits of this material as environmentally friendly in the long run would then be quantifiable. The consistent and sustainable production can be guaranteed by the implementation of industrial-scale bioreactors with mixed plastic feedstocks and microbial consortia (Lei et al., 2021).

The results mark a technology and environment breakthrough; it was proved how high-tech nanomaterials can be created out of waste products and presented a gap between eco-innovation and clean energy production. This is in line with the greater goal of a circular and carbon-neutral economy whereby all materials are constantly regenerated and energy is produced sustainably.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The paper manages to prove how converting post-consumer plastic wastes into high-value energy-generating nanomaterials using a sustainable and innovative strategy could be achieved. The study is a bridge between environmental engineering, biotechnology, and nanomaterial science by processing plastic waste thermally with the help of which carbon-rich substrate can be further used to produce bacterial nanocellulose (BNC). The further functionalization of nanocellulose with platinum nanoparticles resulted in the development of a conductive and permanent electrocatalyst that is effective in energy production.

The resulting material had significant performance characteristics an average conductivity of 0.97 S/cm, power density of 5.16 mW/cm 2 and voltage output of 0.545 V with a great stability (91 percent retention of durability) and a low resistance to charge transfer (approximately 253 O). These values are competitive to the available synthetic catalysts but are added to have the advantage of being eco-friendly and renewable. In addition, the process minimized the emission of CO 2 by more than 20 tons of gas and used almost 2,000 of the units of plastic waste, which is cleaner by nature and cost-effective.

In general, the study will help in developing sustainable material science since it proposes a paradigm of a circular waste-to-energy system - turn pollution into power. Not only does it provide a scalable way of the reduction of plastic pollution, but it also poses a viable option towards carbon-neutral renewable energy systems.

Recommendations

Industrial and Microgrid Scaling

Since the electrochemical performance and environmental advantages are promising, the future research should aim at trying to scale up production of nanocellulose-based electrocatalysts to industrial and decentralized energy system.

- The potential industrial applications of such composites can be using the material on fuel cells, supercapacitors, and hydrogen production, where conductivity and durability are essential.
- Microgrid and community-scale renewable systems would be able to utilize these catalysts to convert bioenergy and produce distributed power especially in off-grid or rural zones.
- When scaling up, it should be aimed at maximizing the cost, automation of production processes, and using bioreactors where the nanocellulose is produced, as part of the use of various plastic wastes.

Exploration of Alternative Metal Nanoparticles

Platinum has a higher catalytic activity, it's expensive, and a rare element. Research in the future ought to consider more plentiful and less expensive metals, like nickel (Ni), palladium (Pd), cobalt (Co), or copper (Cu). Such alternatives may considerably cut down the production costs without changing the conductivity and catalytic activity. The enhancement of charge conduction and catalytical activity can also be achieved by using hybrid nanostructures (NiPd or Co-graphene doped nanocellulose).

Environmental and Economic Assessment

A comprehensive life-cycle assessment (LCA) and techno-economic analysis (TEA) should also be included in the development of additional research required to quantify the long-term environment savings and industry viability. This will be useful in ascertainment that expanding production will not impact the goals of sustainability. The collaboration between waste management industries and renewable energy companies can help enhance the ability to link the research with application.

Statement of Contribution: This study proposes an integrated waste-to-energy route in which pyrolysed post-consumer plastic (PET, PE, PP) is used as the carbon source for the bacterial nanocellulose (BNC) while functionalised with platinum nanoparticles to obtain a conductive, biodegradable electrocatalyst (0.97 S/cm; 5.16 mW/cm²; ~91% retention). The novelty of this pathway is the plastic-to-nanocellulose route, which is scarcely reported. For Geotechnical Engineering, it provides a scalable solution for plastic waste landfill and ground disposal reduction (20.66 t CO_2 saved in the experiments), while also providing a bio-based nanocellulose/pyrolysis-char platform for sustainable ground improvement and soil stabilisation which will be tested in the future.

REFERENCES

[1] Bhattacharjee, J., & Roy, S. (2024). Review on green resources and AI for biogenic solar power. Deleted Journal, 2(1), 457–457. https://doi.org/10.59400/esc.v2i1.457

[2] Cao, X., Hayyat, M., & Henry, J. (2025). Green energy investment and technology innovation for carbon reduction: Strategies for achieving SDGs in the G7 countries. International Journal of Hydrogen Energy, 114, 209–220. https://doi.org/10.1016/j.ijhydene.2025.02.484

[3] Chandak, V. S., & Nagime, P. V. (2025). Synthesis, characterization and applications of silver nanoparticles (Ag-NPs) in the field of electronics and optoelectronics device- A review. Hybrid Advances, 8, 100389. https://doi.org/10.1016/j.hybadv.2025.100389

[4] Chen, L., Yang, M., Chen, Z., Xie, Z., Huang, L., Osman, A. I., Farghali, M., Sandanayake, M., Liu, E., Ahn, Y. H., Al-Muhtaseb, A. H., Rooney, D. W., & Yap, P.-S. (2024). Conversion of waste into sustainable construction materials: A review of recent developments and prospects. Materials Today Sustainability, 27(27), 100930–100930. https://doi.org/10.1016/j.mtsust.2024.100930

[5] Chen, Y.-T., Shao, S.-C., Hsu, C.-K., Wu, I-Wen., Hung, M.-J., & Chen, Y.-C. (2020). Incidence of acute kidney injury in COVID-19 infection: a systematic review and meta-analysis. Critical Care, 24(1). https://doi.org/10.1186/s13054-020-03009-y

[6] Dhillon, S. K., & Kundu, P. P. (2023). Transition metal sulfide/oxide nanoflowers decorated on poly (aniline-2-sulfonic acid) modified polyacrylamide derived carbon cathode catalyst for bioenergy generation in microbial fuel cells. Electrochimica Acta, 461, 142697. https://doi.org/10.1016/j.electacta.2023.142697

[7] Fahey, J. W., Zalcmann, A. T., & Talalay, P. (2001). The chemical diversity and distribution of glucosinolates and isothiocyanates among plants. Phytochemistry, 56(1), 5–51. https://doi.org/10.1016/s0031-9422(00)00316-2

[8] Gezahegn, T. F., Ambaye, A. D., Mekoyete, T. M., Malefane, M. E., Oyedotun, K. O., & Touhami Mokrani. (2024a). Breakthroughs in nanostructured-based chemical sensors for the detection of toxic metals. Talanta Open, 10, 100354–

100354. https://doi.org/10.1016/j.talo.2024.100354

[9] Gezahegn, T. F., Ambaye, A. D., Mekoyete, T. M., Malefane, M. E., Oyedotun, K. O., & Touhami Mokrani. (2024b). Breakthroughs in nanostructured-based chemical sensors for the detection of toxic metals. Talanta Open, 10, 100354–100354. https://doi.org/10.1016/j.talo.2024.100354

[10] H. Birniwa, A., S. Abdullahi, S., Y. Yakasai, M., & Ismaila, A. (2021). Studies on physico-mechanical behaviour of kenaf/glass fiber reinforced epoxy hybrid composites. Bulletin of the Chemical Society of Ethiopia, 35(1), 171–184. https://doi.org/10.4314/bcse.v35i1.15

[11] Hemmat Esfe, M., Amoozadkhalili, F., & Toghraie, D. (2023). Determining the optimal structure for accurate estimation of the dynamic viscosity of oil-based hybrid nanofluid containing MgO and MWCNTs nanoparticles using multilayer perceptron neural networks with Levenberg-Marquardt Algorithm. Powder Technology, 415, 118085. https://doi.org/10.1016/j.powtec.2022.118085

[12] Hernandez-Ortega, J., Ahmed, C., Molina, A., Sabo, R. C., Sanchez, L. E., Bonifacio, B., Cabrera, C. R., & Noveron, J. C. (2025). High-Performance Catalytic Oxygen Evolution with Nanocellulose-Derived Biocarbon and Fe/Zeolite/Carbon Nanotubes. Catalysts, 15(8), 719–719. https://doi.org/10.3390/catal15080719

[13] Huff, C., Biehler, E., Quach, Q., Long, J. M., & Abdel-Fattah, T. M. (2021). Synthesis of highly dispersive platinum nanoparticles and their application in a hydrogen generation reaction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 610, 125734. https://doi.org/10.1016/j.colsurfa.2020.125734

[14] Hughes, A. E., Haque, N., Northey, S. A., & Giddey, S. (2021). Platinum Group Metals: A Review of Resources, Production and Usage with a Focus on Catalysts. Resources, 10(9), 93. https://doi.org/10.3390/resources10090093

[15] Huseen, H. M., Wannas, A. K., & Ajeel, N. S. (2026). Treatment of Heavy Metal Pollution in Bahr Al-Najaf Water Using Green CuO Nanoparticles. Basrah Journal of Agricultural Sciences, 39(1), 417–424. https://bjas.bajas.edu.iq/index.php/bjas/article/view/3117

[16] Huston, M., DeBella, M., DiBella, M., & Gupta, A. (2021). Green Synthesis of Nanomaterials. Nanomaterials, 11(8), 2130. https://doi.org/10.3390/nano11082130

[17] Ieva Plikusiene, Zigmas Balevicius, Almira Ramanaviciene, Talbot, J., Gitana Mickiene, Saulius Balevicius, Arunas Stirke, Tereshchenko, A., Tamosaitis, L., Gintautas Zvirblis, & Arunas Ramanavicius. (2020). Evaluation of affinity sensor response kinetics towards dimeric ligands linked with spacers of different rigidity: Immobilized recombinant granulocyte colony-stimulating factor based synthetic receptor binding with genetically engineered dimeric analyte derivatives. Biosensors and Bioelectronics, 156, 112112–112112. https://doi.org/10.1016/j.bios.2020.112112

[18] Lacrimioara Senila, Kovacs, E., Resz, M.-A., Senila, M., Anca Becze, & Roman, C. (2024). Life Cycle Assessment (LCA) of Bioplastics Production from Lignocellulosic Waste (Study Case: PLA and PHB). Polymers, 16(23), 3330–3330. https://doi.org/10.3390/polym16233330

[19] Lei, Y., Zhang, J., Schiavon, C. R., He, M., Chen, L., Shen, H., Zhang, Y., Yin, Q., Cho, Y., Andrade, L., Shadel, G. S., Hepokoski, M., Lei, T., Wang, H., Zhang, J., Yuan, J. X.-J. ., Malhotra, A., Manor, U., Wang, S., & Yuan, Z.-Y. (2021). SARS-CoV-2 Spike Protein Impairs Endothelial Function via Downregulation of ACE 2. Circulation Research, 128(9), 1323–1326. https://doi.org/10.1161/circresaha.121.318902

[20] Lekshmi, G. S., Tamilselvi, R., Prasad, K., Bazaka, O., Levchenko, I., Bazaka, K., & Mohandas, M. (2021). Growth of rGO nanostructures via facile wick and oil flame synthesis for environmental remediation. Carbon Letters. https://doi.org/10.1007/s42823-021-00244-3

[21] Martín-Lara, M. A., Piñar, A., Ligero, A., Blázquez, G., & Calero, M. (2021). Characterization and Use of Char Produced from Pyrolysis of Post-Consumer Mixed Plastic Waste. Water, 13(9), 1188. https://doi.org/10.3390/w13091188

[22] Nicu, R., Ciolacu, F., & Ciolacu, D. E. (2021). Advanced Functional Materials Based on Nanocellulose for Pharmaceutical/Medical Applications. Pharmaceutics, 13(8), 1125. https://doi.org/10.3390/pharmaceutics13081125

[23] Nur, N. A. A., Purnamanita, P., & Rachman, I. (2021). Characteristics of Presbyopia Patients at Eye Health Center Makassar. Community Research of Epidemiology (CORE), 1(2), 160. https://doi.org/10.24252/corejournal.v1i2.20883

[24] Plast India, P. I. (2025, March 22). Plastindia International University. Plast India. https://plastindia.edu.in/blog/from-waste-to-wealth-innovations-in-plastic-recycling/

[25] R, R., Philip, E., Thomas, D., Madhavan, A., Sindhu, R., Binod, P., Varjani, S., Awasthi, M. K., & Pandey, A. (2021). Bacterial nanocellulose: engineering, production, and applications. Bioengineered, 12(2), 11463–11483. https://doi.org/10.1080/21655979.2021.2009753

[26] Rajeev Roychand, Zafar, M. A., Jacob, M., & Ngo, T. (2025). A Comprehensive Review on the Thermochemical

Treatment of Plastic Waste to Produce High Value Products for Different Applications. Materials Circular Economy, 7(1). https://doi.org/10.1007/s42824-024-00157-2

[27] Rukaramato, R., Babatunde, D., Madanhire, T., Mketo, N., & Magwa, N. (2025). Nanocellulose-based materials for the removal of metal ions, pharmaceuticals, pesticides, dyes, and other pollutants from aqueous environments: A review. Journal of Industrial and Engineering Chemistry, 150, 265–299. https://doi.org/10.1016/j.jiec.2025.05.028

[28] Shah, H. H., Amin, M., Iqbal, A., Nadeem, I., Kalin, M., Soomar, A. M., & Galal, A. M. (2023). A review on gasification and pyrolysis of waste plastics. Frontiers in Chemistry, 10. https://doi.org/10.3389/fchem.2022.960894

[29] Sumini, M., Andrade, G. J. S., Tischer, C. A., Kobayashi, R. K. T., & Nakazato, G. (2024). Production of bacterial cellulose by Komagataeibacter xylinus: biochemistry, synthesis and applications. Cellulose. https://doi.org/10.1007/s10570-024-06179-y

[30] Tayyab, S., Khitab, A., Iftikhar, A., Khan, R. B. N., & Kirgiz, M. S. (2023). Manufacturing of high-performance light-weight mortar through addition of biochars of millet and maize. Waste Disposal & Sustainable Energy, 5(1), 97–111. https://doi.org/10.1007/s42768-023-00135-5

[31] Wang, S.-H., Zhou, X., Zhang, H., Zhou, J.-L., Liu, H.-G., Meng, Z.-Y., Ma, J., Zhang, T.-M., Fan, Z., & Zou, H. (2014). The correction of diurnal effects on CSTAR photometry. Research in Astronomy and Astrophysics, 14(3), 345–356. https://doi.org/10.1088/1674-4527/14/3/008

[32] Wang, Z., Zhao, M.-Y., Wang, J.-W., He, Y.-T., Yang, R.-Q., Ji, J.-Q., Ding, Y., Wang, C., Zhao, Y.-H., Zhang, W.-K., Zhang, D., Liu, Y.-Y., Zhang, G.-D., Yang, T.-Y., Li, Z., & Zhang, L. (2025). The GSK3β inhibitor attenuate APAP-induced liver injury by regulating PGC1α-mediated oxidative stress. International Immunopharmacology, 161, 115070. https://doi.org/10.1016/j.intimp.2025.115070

[33] Wibawa, P. J., Nur, M., Asy'ari, M., & Nur, H. (2020). SEM, XRD and FTIR analyses of both ultrasonic and heat generated activated carbon black microstructures. Heliyon, 6(3), e03546. https://doi.org/10.1016/j.heliyon.2020.e03546

[34] Wiederrecht, G. P., Renaud Bachelot, Xiong, H., Konstantinos Termentzidis, Alexandre Nominé, Huang, J., Kamat, P. V., Rozhkova, E. A., Sumant, A. V., Ostraat, M. L., Jain, P. K., Heckle, C., Li, J., & Pupek, K. (2023). Nanomaterials and Sustainability. ACS Energy Letters, 8(8), 3443–3449. https://doi.org/10.1021/acsenergylett.3c01303

[35] Xiao, B.-H., Xiao, K., Li, J.-X., Xiao, C.-F., Cao, S., & Liu, Z.-Q. (2024a). Flexible electrochemical energy storage devices and related applications: recent progress and challenges. Chemical Science, 15(29), 11229–11266. https://doi.org/10.1039/d4sc02139h

[36] Xiao, B.-H., Xiao, K., Li, J.-X., Xiao, C.-F., Cao, S., & Liu, Z.-Q. (2024b). Flexible electrochemical energy storage devices and related applications: recent progress and challenges. Chemical Science, 15(29), 11229–11266. https://doi.org/10.1039/d4sc02139h

[37] Xu, R., Du, L., Adekoya, D., Zhang, G., Zhang, S., Sun, S., & Lei, Y. (2020). Well-Defined Nanostructures for Electrochemical Energy Conversion and Storage. Advanced Energy Materials, 11(15), 2001537–2001537. https://doi.org/10.1002/aenm.202001537

[38] Xu, Z., Li, L., Chen, X., Fang, C., & Xiao, G. (2021). Mesoporous Zeolitic Imidazolate Frameworks. CCS Chemistry, 1–17. https://doi.org/10.31635/ccschem.021.202101430

[39] Yadav, P., & Samadder, S. (2014). Life cycle assessment of solid waste management options: A Review. Science and Technology, 6(1), 2076–5061. https://www.nswai.org/docs/LCA%20of%20solid%20waste%20management%20options.pdf

[40] Yamunathevi Mathivanan, Shafinaz Shahir, Ibrahim, Z., & Nizam, A. (2024). Fruit Wastes and Crop Residues as Nutrient Sources for Bacterial Nanocellulose Production: A Review. Malaysian Journal of Fundamental and Applied Sciences, 20(5), 1032–1048. https://doi.org/10.11113/mjfas.v20n5.3522