Utilization of Onion Peel Waste as a Sustainable Bio-Based Material for Energy Applications: Structural, Optical, and Electrochemical Characteristics

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ABSTRACT

The valorization of agricultural waste supports the growing demand for sustainable resources in advanced technologies. This study evaluated the structural, optical, chemical, and electrochemical properties of aqueous onion peel waste (*Allium cepa* L.) extract for energy related applications. Onion peel waste was extracted by aqueous maceration, screened for phytochemicals, and characterized using UV–Visible spectroscopy, Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), electrochemical impedance spectroscopy (EIS) and cyclic voltammetry (CV). Screening identified phenolics, flavonoids, tannins, saponins, alkaloids, glycosides, anthraquinones and reducing sugars, confirming abundant electroactive biomolecules. UV–Visible spectroscopy showed strong absorption at 305 nm attributed to conjugated phenolic structures. FTIR identified hydroxyl, carbonyl, aromatic and ether groups responsible for chemical reactivity. SEM revealed an irregular, heterogeneous, aggregated morphology and XRD indicated semi-crystalline features associated with organized phytochemical domains. EDX showed a carbon oxygen-rich composition containing 27.3 wt% carbon and 72.7 wt% oxygen. Electrochemical analysis demonstrated favourable charge transfer, with solution and charge-transfer resistances of 0.4 Ω and 5.8 Ω, respectively, alongside quasi-reversible phenolic redox activity. These findings demonstrate that *Allium cepa* L. peel is a promising renewable precursor for electrode modification and development of sustainable materials for energy conversion and storage technologies.

Keywords: *Allium cepa* L., biomass valorization, phytochemicals, electrochemical properties, sustainable energy materials.

INTRODUCTION

The increasing demand for sustainable and environmentally friendly materials for advanced technological applications has stimulated research into the conversion of agricultural waste into functional materials [1, 2]. Among various biological wastes, onion peel represents an abundant and underutilized biomass rich in organic compounds, cellulose structures, pigments and bioactive molecules [3]. Usually discarded as household and industrial waste [4], onion peel has gained attention due to its high concentration of phenolic compounds, flavonoids, and other functional constituents that contribute to its chemical stability and potential applications in material science. Previous studies have demonstrated that onion peels contain significant amounts of quercetin derivatives, anthocyanins and other polyphenolic compounds, making them promising candidates for sustainable resource utilization and value-added applications [5, 6].

The structural and optical characteristics of plant derived materials play important roles in determining their suitability for functional and energy related applications. The hierarchical biological structure of *Allium cepa* L. peel, consisting of fibrous cellulose networks, layered epidermal tissues and naturally occurring pigments, provides unique morphological and optical properties that may influence light interaction, absorption and charge transport processes. The presence of conjugated phenolic compounds and pigment molecules suggests that onion peel could exhibit useful optical responses including light absorption within the visible region. Such characteristics are particularly relevant in emerging sustainable energy technologies where natural materials are being explored as alternatives or complementary components in photovoltaic and energy harvesting systems. Studies on plant based sensitizers and bio-derived materials have highlighted their potential in renewable energy devices due to their availability, low environmental impact and functional chemical structures [7, 8]. Therefore, characterization of *Allium cepa* L. peel is essential to understand its structural, optical and energy harvesting potentials.

Techniques such as microscopy, spectroscopy and material analysis can provide insights into its surface morphology, chemical composition, optical behaviour and suitability for energy conversion applications. Investigating onion peel as a functional bio-derived material aligns with current efforts toward circular economy approaches where agricultural residues are transformed into valuable materials for sustainable technologies [9,10].

Previous studies have established the potential of onion peel waste as a source of valuable phytochemicals and a precursor for functional materials. Sagar et al [11] reported that onion waste contains quercetin-rich polyphenolic compounds suitable for producing value-added materials, while Islam et al [12] successfully used *Allium cepa* peel extract to synthesize ZnO nanoparticles with antioxidant and antibacterial properties. Similarly, Soumahoro et al [13] employed onion peel extract (OPE) in the green synthesis of Fe_3O_4 nanoparticles for phosphorus removal. Okhuarobo et al [14] investigated onion-peel-mediated MgO nanoparticles for energy harvesting applications. However, these studies focused mainly on synthesized nanoparticles, biological activity or environmental remediation. The structural, optical, chemical, morphological, elemental and electrochemical properties of the aqueous OPE itself have not been comprehensively investigated using complementary characterization techniques. This study fills this gap by directly evaluating aqueous OPE as an electroactive, bio-derived material for sustainable energy conversion, storage and electrode-modification applications.

The aim of this study is to extract and characterize aqueous *Allium cepa* L. peel extract to determine its suitability as a sustainable bio-based material for energy related applications. The specific objectives of this study are to identify the phytochemical constituents of the extract, and to establish relationships among its phytochemical composition, structural features, optical response and electrochemical performance. These objectives provide an assessment of onion peel waste as a renewable precursor for synthesis, electrode modification and sustainable energy materials.

MATERIALS AND METHOD

The chemicals and reagents used in this investigation include Fehlings solution, Benedict reagent, ferric chloride, Chloroform, and Wagners reagent. All the reagents and chemicals were of analytical grades and were not further purified. *Allium cepa L* peel (Plate 1) for the synthesis of nanoparticles of MgO-NPs and FeO--NPs were obtained from Hausa Market in Warri-Sapele Road, Uwvie LGA, Delta State, Nigeria and taxonomically identified in Department of Plant Biology and Biotechnology, University of Benin, Benin City, Edo State, Nigeria. Instruments used include drying oven (LD-201-E vision scientific), heating mantle (HH-W420), UV-Visible spectrophotometer (Perkin Elmer Lambda 40), magnetic stirrer (78-1), centrifuge (CGOLDENWALL 80-2), and a dessicator.

Plate 1: Onion peel waste

Extraction and phytochemical screening of *Allium cepa L* peel extract

Extraction and phytochemical screening were performed in accordance with the procedures laid out by Elemike et al [15] and alshahrani *et al* [14]. The peels were washed in clean water to remove sand and debris. The washed peels were dried in open air for 7 days and pulverized with a standard electric blender. Maceration extraction method was used to obtain OPE by weighing 50 g pulverised *Allium cepa L* peel and 500 mL of distilled water into 2000 L beaker heated with a temperature-regulated magnetic stirrer at 60 ºC for 2 hours. The extracting mixture displayed a colour change in its aqueous solution from watery to dark brown. The extract was separated by filtration, using the Whatman filter paper and stored in polyethylene terephthalate (PET) bottles in order to be used for synthesis of MgO and FeO nanoparticles. The phytochemical analysis was conducted on the water peel extract. The flow diagram of the extraction procedure is shown in Figure 1.

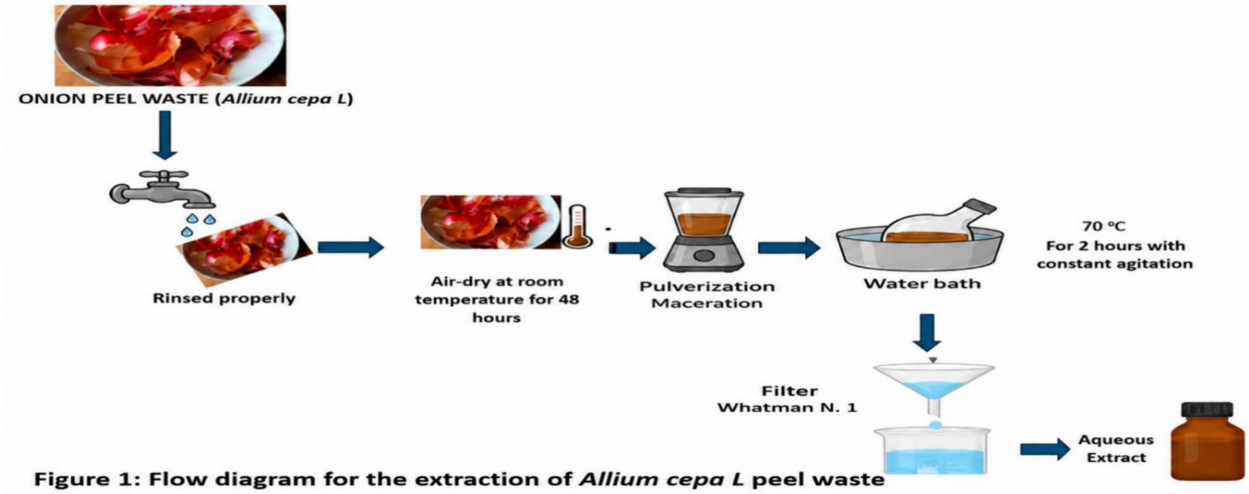


Figure 1: Flow diagram for the extraction of *Allium cepa L* peel waste

Phytochemical analysis

Phytochemical screening for alkaloids, flavonoids, saponins, tannins, phenolics, glycosides, terpenoids, steroids, anthraquinones, reducing sugars and proteins was carried out using standard qualitative procedures [4, 16] as presented in Table 1.

Table 1: Methods of phytochemical analysis of aqueous OPE

Phytochemical	Method
Appearance	Preliminary investigation
Colour Description	Preliminary investigation
Flavonoids	Alcl$_3$ Test, Shinoda test
Phenolic Compounds	Fecl$_3$ test, Folin-Ciocalteu
Organosulfur Compounds	Lead Acetate Test
Tannins	Fecl$_3$ test
Saponins	Foam Test
Reducing Sugars	Benedict's Test, Fehling's test
Glycosides	Molisch's test
Alkaloids	Wagner's, Dragendorff's
Steroids	Liebermann-Burchard test
Terpenoids	Salkowski test
Carbohydrates	Iodine test

Characterization of nanomaterials

The synthesized nanomaterials were analyzed using UV-Visible spectrophotometry to determine its optical absorption behaviour; identify its principal functional groups through FTIR analysis; examine its surface morphology, crystallinity and elemental composition using SEM, XRD, and EDX, respectively; evaluate its charge-transfer characteristics and redox behaviour using electrochemical impedance spectroscopy and cyclic voltammetry.

RESULTS AND DISCUSSION

Phytochemical analysis of aqueous OPE

The phytochemical composition of aqueous onion (*Allium cepa* L.) peel extract is highly relevant to energy related studies, particularly in the development of sustainable materials for renewable energy conversion and storage technologies. As shown in Table 2, the detection of phenolic compounds, flavonoids, tannins, saponins, alkaloids, glycosides, reducing sugars and anthraquinones indicates the presence of diverse functional molecules capable of participating in redox reactions. These bioactive compounds contain hydroxyl, carbonyl and other electron-donating functional groups that can facilitate metal-ion reduction and surface modification during the green synthesis of energy-related nanomaterials. The dark brown colour of the extract further suggests a high concentration of polyphenolic compounds, which are associated with strong antioxidant activity and electron-transfer capabilities. Such properties are beneficial in preparing metal oxide nanoparticles and carbon-based materials used in photocatalysis, supercapacitors, batteries and other energy conversion systems [14, 17,18].

The abundance of phenolic compounds, flavonoids and tannins in OPE plays an important role in energy material synthesis because these compounds can act as natural reducing, chelating and stabilizing agents. During the biosynthesis of metal and metal oxide nanoparticles, phenolic hydroxyl groups can donate electrons to metal ions, promoting nucleation and particle formation while their antioxidant nature helps control oxidation processes and improve material stability. In energy applications, phytochemically synthesized nanoparticles such as iron oxide, zinc oxide and titanium dioxide have attracted significant attention due to their enhanced electrical, optical and catalytic properties for applications including lithium-ion batteries, supercapacitors, fuel cells, and photocatalytic hydrogen production. The presence of saponins and glycosidic compounds may also improve nanoparticle dispersion by acting as natural capping agents, reducing aggregation and producing materials with improved surface area and electrochemical performance [19, 20].

The presence of reducing sugars, alkaloids, anthraquinones and glycosides further highlight the potential of OPE as a renewable biochemical resource for energy material fabrication. Reducing sugars and polyphenolic compounds can provide electrons during green synthesis reactions while carbon-rich organic components derived from plant extracts can serve as precursors for functional carbon materials used in energy storage devices. For example, biomass-derived carbon materials produced from agricultural wastes have been investigated as electrode materials because of their porous structures, high surface areas, and sustainable origin. Although carbohydrates were not detected in the present phytochemical screening, the presence of carbohydrate-derived metabolites such as reducing sugars and glycosides suggests the availability of organic constituents capable of contributing to carbonaceous material formation.

Therefore, the phytochemical profile of aqueous OPE supports its potential application as an environmentally friendly reducing and stabilizing agent for the synthesis of advanced energy materials, contributing to the development of low-cost and sustainable technologies for energy storage and conversion [21-23].

Table 2: Phytochemical analysis of aqueous OPE

Test performed	Results
Appearance	Liquid
Colour description	Dark brown
Saponin	+
Reducing sugar	+
Alkaloids	+
Tannins	+
Anthraquinones	+
Phenolic compounds	+
Carbohydrates	-
Flavonoids	+
Glycosides	+
Tannins	+

Keys: (+) Present, (-) Absent

UV-Vis Spectroscopy of OPE

The UV–Vis absorption spectrum of the aqueous onion peel extract exhibited a strong absorption band with a maximum absorbance (Amax) of approximately 2.74 a.u. at λmax of 305 nm followed by a gradual decrease in absorbance across the visible region (300–800 nm) (Figure 2). The intense absorption peak in the near-UV region can be attributed to electronic transitions associated with aromatic phenolic structures, particularly flavonoids, phenolic acids and quercetin derivatives present in OPE. Onion skins are known to contain high concentrations of flavonols, especially quercetin and its glycosides, which exhibit characteristic UV absorption bands resulting from $\pi \rightarrow \pi^*$ transitions of conjugated aromatic systems. The observed absorption around 305 nm is therefore consistent with the presence of polyphenolic compounds identified during phytochemical screening, including phenolics and flavonoids. Similar UV–Vis characteristics have been reported for OPEs, where absorption bands within the 300–380 nm range were associated with flavonoid structures and quercetin derivatives [11]. The progressive decline in absorbance toward longer wavelengths indicates reduced absorption by conjugated chromophores in the extract. The strong UV absorption response further supports the antioxidant and electron-donating capability of onion peel phytochemicals, which is highly beneficial for green synthesis applications, particularly in the preparation of metal and metal oxide nanomaterials for energy conversion and storage systems. Phenolic compounds such as quercetin possess hydroxyl functional groups capable of electron transfer and metal-ion reduction, making OPEs effective natural reducing and stabilizing agents [21].

Therefore, the UV–Vis profile confirms the successful extraction of bioactive polyphenolic compounds from onion peel and highlights its potential as a sustainable biochemical precursor for energy-related nanomaterial synthesis.

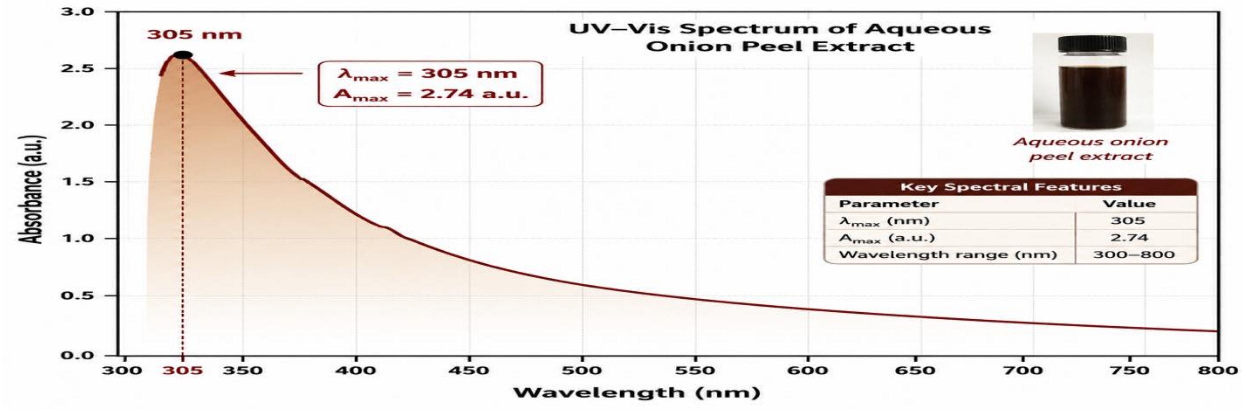


Figure 2: OPE UV-Vis Spectroscopy

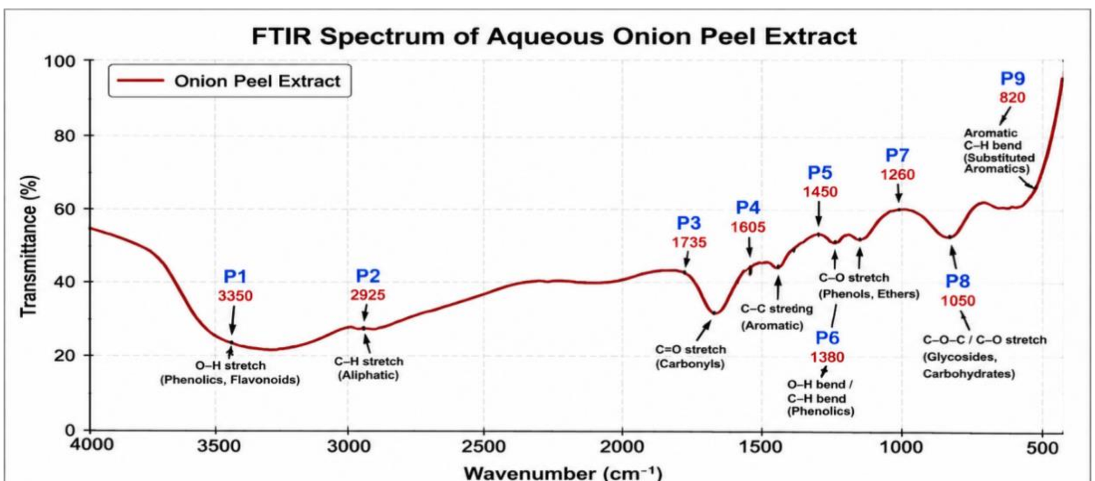
FTIR spectrum of OPE

The FTIR spectrum of the aqueous onion peel extract in Figure 3 reveals several characteristic absorption bands corresponding to functional groups associated with phytochemical constituents. A broad absorption band observed around 3350 cm⁻¹ (P1) was assigned to O–H stretching vibrations, indicating the presence of hydroxyl-containing compounds such as phenolics, flavonoids and tannins. The weak band near 2925 cm⁻¹ (P2) corresponded to C–H stretching vibrations of aliphatic groups while the absorption peak around 1735 cm⁻¹ (P3) was attributed to C=O stretching vibrations from carbonyl-containing compounds such as organic acids and flavonoid derivatives. The peak observed at approximately 1605 cm⁻¹ (P4) was associated with aromatic C=C stretching vibrations, confirming the presence of conjugated aromatic structures characteristic of polyphenolic compounds, particularly quercetin derivatives. Onion peel is widely recognized as a rich source of quercetin, quercetin glycosides, and other phenolic compounds, which contribute to its strong antioxidant and electron-donating properties.

Additional bands within the fingerprint region, including peaks around 1450 cm⁻¹ (P5), 1380 cm⁻¹ (P6), 1260 cm⁻¹ (P7), and 1050 cm⁻¹ (P8), were assigned to C–H bending, O–H deformation, C–O stretching, and C–O–C vibrations, respectively. These functional groups are commonly associated with phenolic ethers, flavonoid glycosides, reducing sugars, and other oxygenated phytochemicals present in OPE. The absorption near 820 cm⁻¹ (P9) corresponds to aromatic C–H bending vibrations, further supporting the presence of substituted aromatic compounds. These FTIR features agree with recent studies reporting that OPEs contain diverse polyphenolic compounds, including flavanols, flavones, anthocyanins, and phenolic acids, which are responsible for their antioxidant activity and chemical reactivity [24].

The identified functional groups demonstrate the chemical suitability of aqueous OPE as a natural reducing and stabilizing agent for green synthesis applications, particularly in energy-related nanomaterial development. Hydroxyl, carbonyl and ether-containing groups can participate in electron transfer, metal-ion reduction and surface interaction processes during nanoparticle formation. These characteristics are particularly important in the fabrication of metal oxide nanomaterials for applications such as supercapacitors, batteries, photocatalysts and other sustainable energy technologies.

The FTIR results confirm the successful extraction of bioactive phytochemicals from onion peel waste and highlight its potential as a renewable biochemical precursor for advanced functional materials. Recent investigations have similarly emphasized onion peel waste as a valuable source of quercetin-rich extracts and antioxidant molecules for sustainable material and industrial applications [5, 25].



Peak No.	Wavenumber (cm^{-1})	Functional Group	Vibrational Assignment	Possible Phytochemical Origin
P1	3350	O–H	O–H stretching	Phenolics, Flavonoids, Tannins
P2	2925	C–H	C–H stretching	Aliphatic hydroaarbons
P3	1735	C=O	C=O stretching	Carbonyl compounds, Organic acids
P4	1605	C=C	Aromatic C–C stretching	Aromatic rings, Quercetin derivatives
P5	1450	C–H	C–H bending	Aliphatic / Phenolic structures
P6	1380	O–H / C–H	O–H deformation / C–H bending	Phenolic compounds
P7	1260	C–O	C–O stretching	Phenols, Ethers, Flavonoids
P8	1050	C–O–C / C–O	C–O–C / C–O stretching	Glycosides, Polysaccharides
P9	820	Ar–H	Aromatic C–H bending	Substituted aromatic compounds

All peak positions are ±2 cm^{-1} tolerance.

Figure 3: FTIR Spectrum of OPE

Morphological analysis

The scanning electron microscopy of the OPE

The SEM image of the aqueous onion peel in Figure 4 recorded at 200× magnification and an accelerating voltage of 20 kV reveals an irregular and heterogeneous surface morphology characterized by aggregated particles, fragmented structures and rough-textured features. The micrograph shows the presence of non-uniform particles with irregular plate-like and granular morphologies distributed throughout the matrix, suggesting the complex nature of the dried phytochemical-rich extract. The observed agglomeration may be attributed to strong intermolecular interactions among polyphenolic compounds, flavonoids, tannins, and other biomolecules present in onion peel, which can promote particle clustering during drying and sample preparation. Similar irregular aggregated morphologies have been reported for plant-derived extracts, where the presence of organic constituents and high surface energy contributes to non-uniform particle arrangements [16].

The rough surface texture and heterogeneous particle distribution observed in the SEM micrograph are consistent with the presence of diverse phytochemical constituents identified through phytochemical screening and FTIR analysis including phenolic compounds, flavonoids, glycosides and oxygen-containing functional groups. These biomolecules can adsorb onto particle surfaces through hydroxyl, carbonyl and ether functionalities, influencing surface morphology and providing potential active sites for chemical interactions.

Previous studies using OPEs have demonstrated that bioactive polyphenols, particularly quercetin derivatives, participate in metal-ion reduction and surface stabilization during nanoparticle synthesis, resulting in improved morphological control. Furthermore, the presence of micron-sized irregular fragments alongside smaller particulate domains indicates that the OPE possesses a complex carbonaceous and organic matrix, which is advantageous for energy-related material development. Such heterogeneous structures can provide abundant surface functional groups and active sites, which are beneficial for applications involving adsorption, catalytic reactions, electrode modification and preparation of biomass-derived carbon materials for energy storage systems.

The SEM findings confirm the successful formation of a phytochemical-rich, structurally diverse OPE and support its suitability as a sustainable precursor for green synthesis of functional nanomaterials and energy-related applications. Recent investigations have similarly highlighted onion peel waste as a valuable renewable resource for producing functional materials due to its high polyphenol content and ability to act as a biological reducing/stabilizing medium [16].

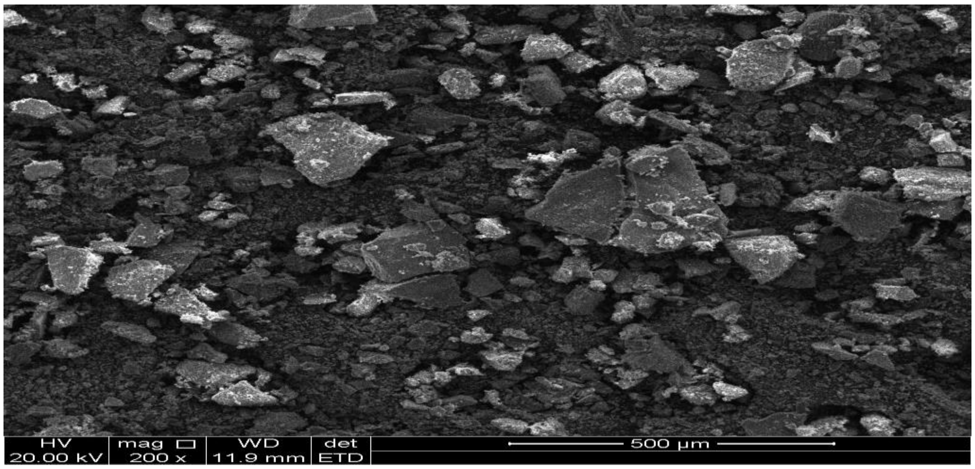


Figure 4: The scanning electron microscopy image of OPE

X-ray diffraction analysis

The XRD pattern of the aqueous OPE in Figure 5 exhibits several distinct diffraction peaks at approximately 2θ values corresponding to the indexed planes (023), (200), (213), (153), (037) and (332) indicating the presence of crystalline organic and inorganic domains within the extract matrix. The most intense reflection observed at the (023) plane suggests a dominant crystalline orientation while the additional diffraction peaks confirm the semi-crystalline nature of the extract.

The presence of multiple diffraction reflections can be associated with the complex arrangement of phytochemical constituents including polyphenols, flavonoids, glycosides and other biomolecular components present in onion peeas proven by phytochemical analysis. These compounds can form ordered molecular arrangements through hydrogen bonding and intermolecular interactions, contributing to the observed crystalline features. Similar XRD behaviour has been reported for plant-derived extracts, where diffraction peaks arise from naturally occurring crystalline phytoconstituents and biomolecular assemblies [26].

The relatively broad diffraction features and background scattering observed in the XRD pattern suggest the coexistence of crystalline and amorphous phases, which is typical of biomass-derived materials containing organic macromolecules. The amorphous contribution is mainly attributed to polymeric components such as polysaccharide derivatives, lignocellulosic residues and other non-crystalline phytochemical fractions, whereas sharper peaks originate from ordered molecular structures. This combination of crystalline and amorphous characteristics is advantageous for green synthesis applications because the amorphous organic matrix provides abundant functional groups for metal-ion interaction while crystalline domains contribute to structural stability. The observed diffraction pattern further supports the suitability of OPE as a sustainable precursor for advanced functional materials particularly in energy-related applications.

The aromatic and oxygen-containing phytochemicals identified through FTIR analysis can facilitate nucleation, surface modification and stabilization during the synthesis of metal oxide nanoparticles, influencing their crystallinity and electrochemical performance. In energy storage systems, crystalline phases and controlled structural ordering are critical factors affecting charge transport, ion diffusion and catalytic activity.

Therefore, the XRD profile of OPE confirms the presence of structurally organized phytochemical components and highlights the potential of onion peel waste as a renewable bioresource for the development of green-synthesized electrode materials, photocatalysts and other energy conversion/storage materials. Recent investigations have similarly emphasized OPE as an effective biological medium for synthesizing crystalline ZnO, Ag, and other functional nanoparticles due to its rich phytochemical composition.

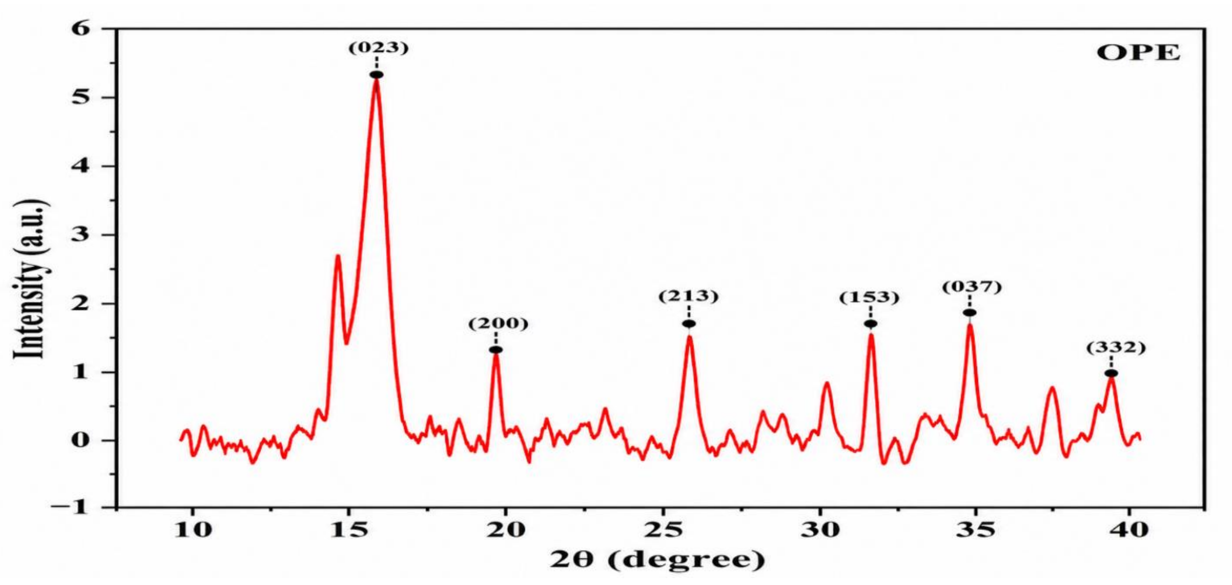


Figure 5: XRD analysis of OPE

Table 3: Crystallite size calculation for OPE from XRD spectrum

B3- CALCULATION TABLE (OPE)						
Peak position (2θ)	hkl	FWHM (β)	Angle (radian)	FWHM(radian)	Crystalline size	Average Size
17.21735	8.608675	0.96546	0.15025	0.01685	8.322262	21.23392
20.91533	10.45767	0.26227	0.182521	0.004577	30.80214	
26.91681	13.45841	0.43976	0.234893	0.007675	18.57515	
32.50873	16.25437	0.24618	0.283692	0.004297	33.61384	
35.2888	17.6444	0.41713	0.307953	0.00728	19.9853	
39.22713	19.61357	0.52367	0.342321	0.00914	16.10485	

Energy dispersive X-ray analysis

The EDX analysis of the aqueous onion (*Allium cepa* L.) peel extract in figure 6 revealed the presence of predominantly oxygen (O, 72.7 wt%) and carbon (C, 27.3 wt%), confirming the organic and oxygenated nature of the biomass-derived material. The high oxygen content indicates the abundance of oxygen-containing functional groups, such as hydroxyl (–OH), carbonyl (C=O) and ether (C–O–C) groups, which is consistent with the FTIR results and the presence of phenolic compounds, flavonoids, tannins and glycosidic constituents identified through phytochemical screening. The carbon signal represents the carbonaceous framework of the onion peel matrix, originating from polyphenols, lignocellulosic components and other organic metabolites. Similar C and O elemental profiles have been reported for plant-mediated materials, where carbon and oxygen are derived from phytochemical constituents that act as natural reducing and stabilizing agents during green synthesis processes [27].

Therefore, the EDX findings validate the successful extraction of carbon–oxygen-rich bioactive compounds from onion peel waste and support its potential utilization as a sustainable precursor and green chemical mediator for energy material development.

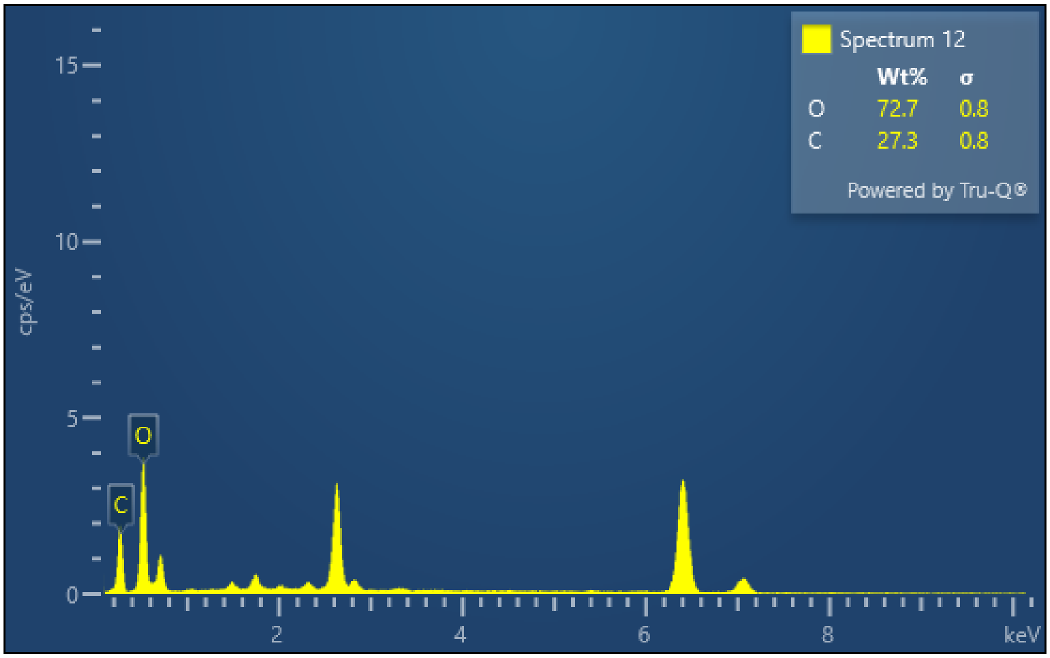


Figure 6: The Energy dispersive X-ray spectrum of OPE

Electrochemical performance of OPE

Electrochemical Impedance Spectroscopy Analysis of OPE (Nyquist plot)

The Nyquist plot of the aqueous OPE in Figure 7 exhibits a depressed semicircular profile in the high to medium frequency region, indicating a charge-transfer-controlled electrochemical process. The estimated solution resistance (Rs) of approximately 0.4 Ω reflects good ionic conductivity and low uncompensated resistance within the electrolyte system. The semicircle diameter corresponds to a charge-transfer resistance (Rct) of approximately 5.8 Ω, suggesting efficient interfacial electron-transfer kinetics (Ren et al., 2024). The relatively low Rct value may be attributed to the presence of oxygenated phytochemical functionalities, including hydroxyl, carbonyl and ether groups from phenolic compounds, flavonoids and glycosides identified in the OPE. These functional groups can enhance electrolyte interaction and facilitate charge-transfer processes through improved surface wettability and electron transport pathways. Similar low-resistance behaviour has been reported for biomass-derived carbonaceous and phytochemical-based materials used in electrochemical energy applications, where abundant oxygen-containing surface groups contribute to enhanced electrochemical activity and reduced interfacial resistance [22, 27].

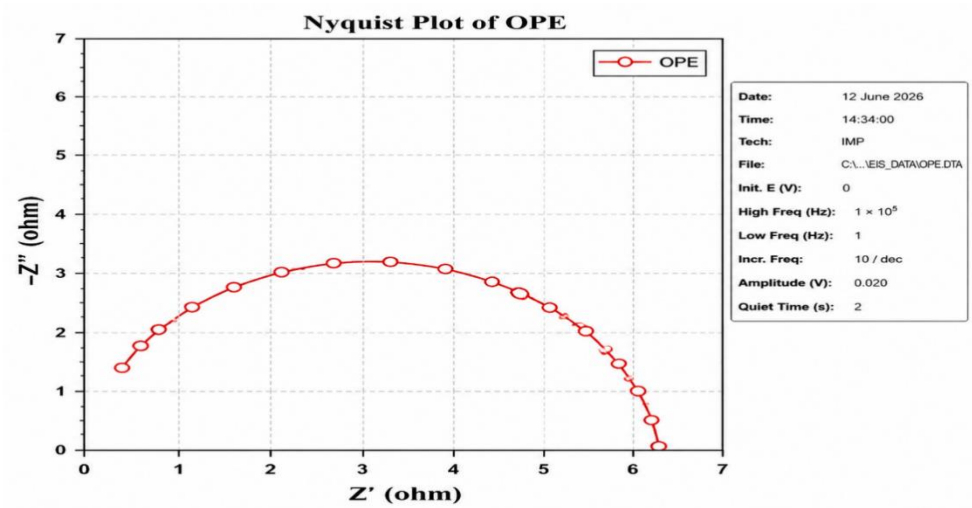


Figure 7: Electrochemical Impedance Spectroscopy Analysis of OPE (Nyquist plot)

From the presented Nyquist spectrum:

High-frequency intercept with Z′ axis≈0.4Ω
This corresponds to the solution/ohmic resistance (Rs).

Low-frequency intercept with Z′ axis ≈ 6.2 Ω
This corresponds to Rs + Rct.
Therefore:

$$R_{ct} = (R_s + R_{ct}) - R_s$$

$$R_{ct} = 6.2 - 0.4$$

$$\boxed{R_{ct} \approx 5.8\ \Omega}$$

Parameter	Estimated value
Solution resistance (Rs)	0.4 Ω
Charge-transfer resistance (Rct)	5.8 Ω
Total semicircle resistance (Rs + Rct)	6.2 Ω

Cyclic voltammetry analysis of aqueous OPE

The cyclic voltammetry response of the aqueous onion peel extract in Figure 8 recorded within a potential window of −1.0 to +1.0 V at a scan rate of 0.05 V s^{-1} demonstrates well-defined anodic and cathodic electrochemical features, indicating the presence of electroactive phytochemical constituents. The voltammogram shows oxidation and reduction peaks associated with reversible or quasi-reversible redox transitions of phenolic compounds, flavonoids and other oxygen-containing biomolecules present in the OPE. The anodic peak observed at approximately Ep,a = +0.253 V with a peak current of Ipa = 1.232×10^{-3} A can be attributed to oxidation of electron-donating functional groups, particularly hydroxyl groups in polyphenolic compounds such as quercetin derivatives. The cathodic peak observed at approximately Ep,c = −0.101 V with Ipc = -3.572×10^{-3} A indicates the corresponding reduction process, suggesting electrochemical activity arising from reversible redox reactions of phytochemical components.

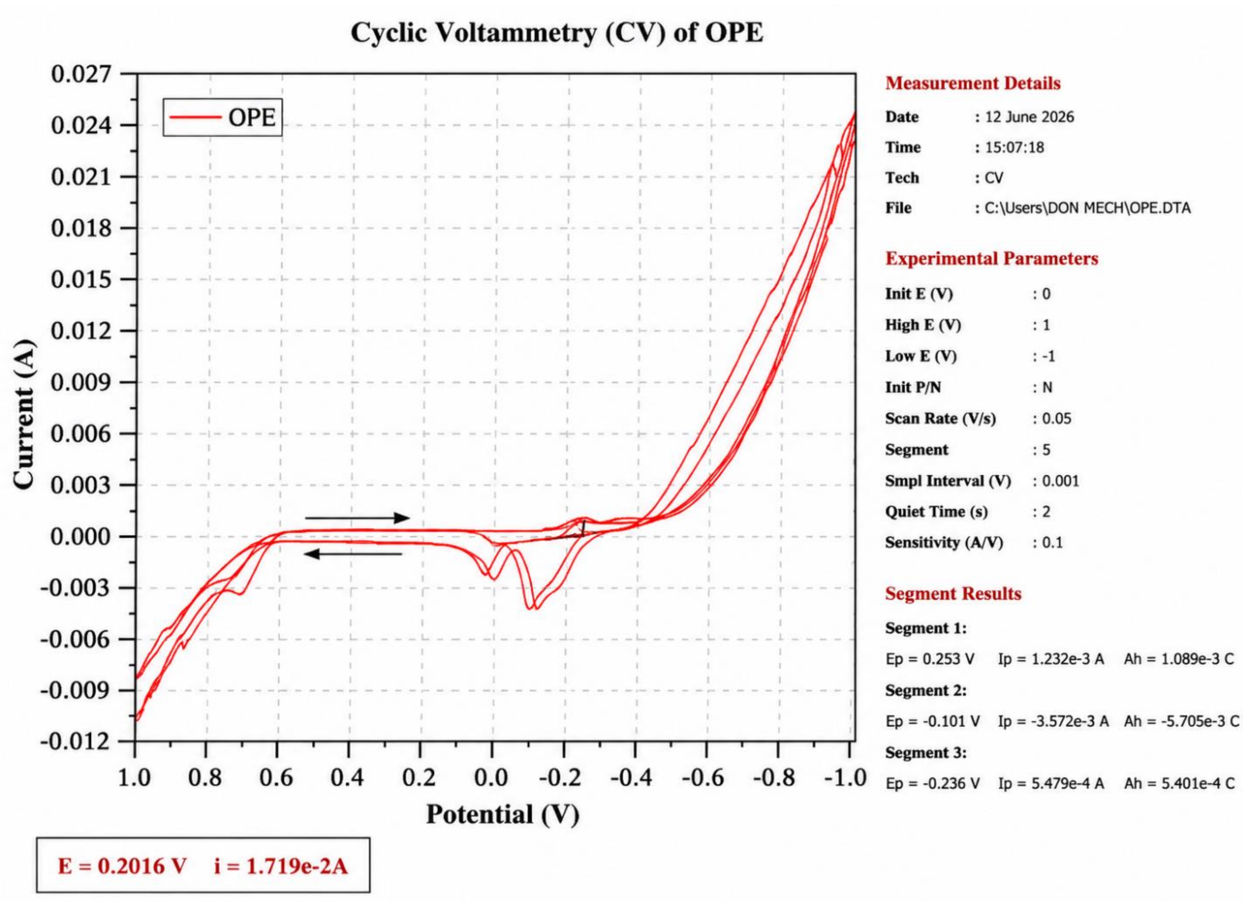


Figure 8: The cyclic voltammetry profile of OPE

Calculated Electrochemical Parameters

1. Peak-to-Peak Separation (ΔEp)

The peak separation is calculated as:

$$\Delta E_p = E_{pa} - E_{pc}$$

$$\Delta E_p = 0.253 - (-0.101)$$

$$\boxed{\Delta E_p = 0.354\ V}$$

A ΔEp value of approximately 354 mV indicates a quasi-reversible electron-transfer process, where electron transfer kinetics are influenced by diffusion, molecular structure and resistance at the electrode/electrolyte interface.

2. Formal Redox Potential (E°′)

The formal potential is estimated as:

$$E^{0'} = \frac{E_{pa} + E_{pc}}{2}$$

$$E^{0'} = \frac{0.253 + (-0.101)}{2}$$

$$\boxed{E^{0'} = 0.076\ V}$$

The formal potential of approximately +0.076 V indicates the redox activity of phenolic antioxidant species within the extract.

3. Peak Current Ratio

The anodic-to-cathodic current ratio is:

$$\frac{|\ I_{pa}\ |}{|\ I_{pc}\ |}$$

$$= \frac{1.232 \times 10^{-3}}{3.572 \times 10^{-3}}$$

$$\boxed{\frac{I_{pa}}{I_{pc}} = 0.35}$$

The deviation from unity indicates a quasi-reversible system with possible contributions from chemical reactions following electron transfer.

4. Electroactive Surface Charge (from Integrated Area)

The instrument reports:

i. Segment 1 charge:

$$Q_a = 1.089 \times 10^{-3} C$$

ii. Segment 2 charge:

$$Q_c = -5.705 \times 10^{-3} C$$

The charge ratio:

$$\frac{|Q_c|}{Q_a} = \frac{5.705 \times 10^{-3}}{1.089 \times 10^{-3}} \boxed{= 5.24}$$

The higher cathodic charge suggests additional reduction reactions or adsorption effects associated with oxygenated phytochemical species.

The cyclic voltammetry profile of aqueous OPE demonstrates significant electrochemical activity arising from the oxidation and reduction of bioactive phytochemicals. The observed anodic and cathodic peaks at +0.253 V and −0.101 V, respectively, correspond to redox transitions involving phenolic hydroxyl groups, flavonoids, and other electron-rich compounds present in the extract. The calculated peak separation (ΔEp = 354 mV) indicates a quasi-reversible electron-transfer mechanism, suggesting moderate charge-transfer kinetics between the electroactive molecules and the electrode surface. The calculated formal potential (E°′ = 0.076 V) confirms the ability of onion peel phytochemicals to participate in oxidation–reduction reactions, which is associated with their antioxidant and electron-donating properties. These characteristics are linked to the presence of quercetin derivatives and oxygen-containing functional groups identified by FTIR and EDX analyses. Similar electrochemical behaviour has been reported for plant-derived polyphenolic extracts, where phenolic compounds contribute to redox activity through reversible proton-coupled electron-transfer mechanisms [21]. The electroactive nature of OPE suggests its potential application as a green reducing agent and biofunctional component in the development of energy-related materials, including electrode modifiers, supercapacitor materials, and metal oxide nanocomposites [27, 28].

Table 4: Summary of Calculated CV Parameters

Parameter	Value
Scan rate	0.05 V s^{-1}
Potential window	−1.0 to +1.0 V
Anodic peak potential (E_{pa})	+0.253 V
Cathodic peak potential (E_{pc})	−0.101 V
Peak separation (ΔE_p)	0.354 V
Formal potential ($E°'$)	0.076 V
Anodic peak current (I_{pa})	1.232×10^{-3} A
Cathodic peak current (I_{pc})	-3.572×10^{-3} A
Current ratio (I_{pa}/I_{pc})	0.35
Oxidation charge	1.089×10^{-3} C
Reduction charge	-5.705×10^{-3} C

CONCLUSION

This study demonstrated that *Allium cepa L.* peel, an abundant agricultural waste material, possesses significant structural, optical, phytochemical and electrochemical properties that support its potential application in sustainable material development. The phytochemical analysis confirmed the presence of bioactive compounds including phenolics, flavonoids, tannins, saponins, alkaloids, glycosides, reducing sugars and anthraquinones, which contribute to its reducing, stabilizing and electron-transfer capabilities. Spectroscopic and morphological analyses further revealed the presence of functional groups, heterogeneous surface structures and carbon–oxygen-rich components suitable for green synthesis and energy-related applications. The XRD and EDX results confirmed the semi-crystalline nature and organic composition of the extract, highlighting its suitability as a renewable precursor for functional materials. Furthermore, the electrochemical studies revealed promising charge-transfer behaviour and redox activity, demonstrating the potential of OPE as a bio-based component for energy conversion and storage technologies.

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