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Review of raman spectral characteristics of graphene derived from 10 types of biomass

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ABSTRACT

Graphene is a structure of carbon atoms arranged in a two-dimensional hexagonal shape. The main raw material for graphene synthesis is graphite. Where the source of graphite that is most often synthesized to produce graphene generally comes from mined graphite and biomass graphite. The raw materials include palm shells, coconut shells, sugar cane, walnut shells, commercial graphite, *Quercus ilex*, coffee, PMDS/Lignin, empty palm fruit bunches and tea. Graphene characteristics can be identified by Raman characteristic curves to determine the D and G peak values of certain graphene structures. This article discusses the Raman characteristics of graphene synthesized from 10 biomasses. Based on research conducted between 2020 and 2024, it was found that the I_D/I_G ratio for various materials showed significant variations, with commercial graphite having the lowest value of 0.09, indicating very high crystallinity. *Quercus ilex* had a ratio of 0.82, followed by coconut shell with 0.85 and walnut shell with 0.98, indicating a relatively regular structure. Palm oil shells show variations in the I_D/I_G ratio from 1.04 to 1.30, while empty palm fruit bunches are at 1.0. Ingredients such as sugar cane and tea have ratios of 1.34 and 1.4 respectively. Coffee has a fairly high ratio, namely 1.78, and PMDS/Lignin has the highest value of 1.86, indicating the most amorphous structure among all the materials analyzed. There are many ways to apply graphne, one of which is making ink.

Keywords: Biomass precursors; graphene; I_D/I_G ratio; palm-coconut biomass; raman spectroscopy

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INTRODUCTION

Palm oil shells represent one of the major solid residues generated in large quantities by the palm oil industry, particularly in major producing countries such as Indonesia and Malaysia [1]. These shells are naturally rich in carbon, the fundamental element required for graphene formation. Utilizing palm shells as a carbon source for graphene not only addresses industrial waste challenges but also provides added value to the agricultural sector while contributing to environmental sustainability [2].

Graphene, widely regarded as one of the most revolutionary materials of the 21st century, has gained significant scientific and technological attention across multiple disciplines [3]. Comprising a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice, graphene exhibits exceptional electrical and thermal conductivity, high mechanical strength, and outstanding surface properties. These characteristics enable its extensive potential applications in electronics, energy storage systems, sensing devices, and advanced composite materials [4].

The conversion of palm oil shells into graphene offers both environmental and economic advantages. The use of biomass-derived carbon precursors reduces the ecological footprint associated with industrial waste while simultaneously lowering the high production costs typically required for graphene synthesis [5]. The transformation process generally involves several key steps, including carbonization to produce activated carbon, chemical exfoliation to separate graphene layers, and reduction treatments to obtain high-quality graphene structures [6]. This approach demonstrates a promising sustainable pathway

for producing functional graphene materials from abundant agricultural biomass.

RESEARCH METHODS

This review article employs a structured qualitative approach to analyze Raman spectroscopic characteristics of graphene synthesized from various biomass precursors. Relevant studies published between 2020 and 2024 were identified through systematic searches in Scopus, Web of Science, ScienceDirect, and Google Scholar using keywords related to biomass-derived graphene and Raman analysis. Only publications reporting experimental synthesis and providing measurable Raman parameters–specifically the D-band (f_D), G-band (f_G), and the I_D/I_G ratio–were included to ensure analytical reliability.

Raman data extracted from each study were standardized and compared to evaluate structural disorder, graphitization quality, and precursor-dependent variations. Additional attention was given to synthesis conditions such as pyrolysis temperature, activation treatment, and chemical exfoliation, which can influence spectral outcomes. The analysis aimed to establish relationships between biomass precursor characteristics and the resulting graphene quality, using commercial graphite as a reference for high crystallinity and more defect-rich materials (e.g., coffee waste and PMDS/lignin) as upper bounds of disorder.

Although variability in synthesis protocols and Raman measurement conditions introduced some limitations, the systematic review approach provided a coherent and comparative understanding of the structural performance of biomass-derived graphene. This method effectively highlights the potential of sustainable precursors–particularly palm kernel shells–for producing environmentally friendly graphene with competitive structural properties.

RESULTS AND DISCUSSION

Graphene is a two-dimensional material composed of a single layer of carbon atoms arranged in a hexagonal lattice, a configuration responsible for its exceptional mechanical, electrical, and thermal properties [4]. Since its first successful isolation by Andre Geim and Konstantin Novoselov in 2004—an achievement that earned the 2010 Nobel Prize in Physics—graphene has become one of the most studied advanced materials worldwide [17]. Its extraordinary thinness, superior strength, high electron mobility, and significant optical transparency have positioned graphene at the forefront of technological innovation, with applications expanding into electronics, energy storage, sensing, biomedicine, and lightweight structural composites [18, 19].

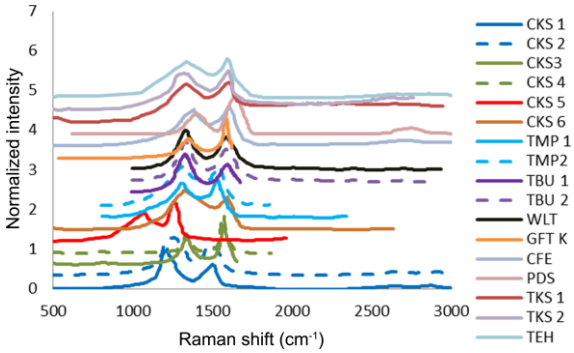

Figure 1. Raman spectroscopy of 10 biomass.

The synthesis of graphene from biomass precursors represents a growing trend toward sustainable and environmentally conscious material production. Coconut shell–derived graphene is a prominent example of this trajectory. Its carbon-rich lignocellulosic structure enables the formation of graphene with mechanical robustness, high electrical and thermal conductivity, and performance characteristics comparable to conventionally produced graphene [20, 21]. Beyond its structural advantages, coconut shell biomass offers substantial environmental benefits, including waste reduction, resource valorization, and support for circular economy models. This strengthens its value as a precursor for eco-friendly graphene manufacturing.

Sugarcane bagasse has also emerged as a promising renewable precursor for sustainable graphene synthesis [9]. Its abundant cellulose

and hemicellulose content provide a suitable carbon framework for generating graphene with strong mechanical integrity and high conductivity. The conversion of sugarcane waste into graphene not only minimizes reliance on fossil-based carbon sources but also enhances industrial waste management. Consequently, sugarcane-derived graphene holds considerable promise for applications in electronics, supercapacitors, and multifunctional composite materials [22].

Table 1. I_D/I_G, F_D, F_G values of 10 biomass.

Notation	Raw material	f_D	f_G	I_G/I_D	Reference
CKS 1	Palm kernel shell	1372	1584	1.04	[7]
CKS 2	Palm kernel shell	1334.22	1569.64	1.17	[1]
CKS 3	Palm kernel shell	1350	1595	1.30	[2]
CKS 4	Palm kernel shell	1324	1591	1.20	[3]
TMP 5	Coconut shell	1524.35	1298.99	0.85	[8]
TBU	Sugarcane	1326	1593	1.34	[9]
WLT	Walnut shell	1349.16	1578.52	0.98	[10]
GFT K	Commercial graphite	1355	1585	0.09	[11]
QI	*Quercus ilex*	1354	159	0.82	[12]
CFE	Coffee	1594.3	1350.44	1.78	[13]
PDS	PMDS/lignin	1580	1350	1.86	[14]
TKS 2	Empty oil palm bunches	1583.41	1300.79	1.0	[15]
THE	Tea	159.5	1337.7	1.4	[16]

Walnut shell–derived graphene further demonstrates the potential of agricultural waste as a precursor for high-value carbon materials. Its naturally dense and aromatic biomass composition allows the formation of graphene with high mechanical strength and excellent electrical conductivity [10]. As a renewable and biodegradable material, walnut shell biomass offers both ecological and economic advantages, making it a competitive alternative to graphite-based graphene synthesis. The structural quality of walnut-derived graphene supports a wide spectrum of advanced technological applications, confirming its strong potential for future material development [23].

Commercial graphite remains the most conventional and efficient precursor for high-quality graphene production, typically yielding highly crystalline graphene through exfoliation techniques [11]. Its natural structural uniformity results in graphene with superior conductivity, exceptional structural ordering, and consistent performance across applications [24]. Although cost and scalability remain ongoing challenges, graphite-derived graphene continues to serve as an industry benchmark, providing a baseline for evaluating biomass-based alternatives.

A similarly promising sustainable precursor is Quercus ilex (Holm oak), whose biomass offers a balanced carbon matrix suitable for producing high-quality graphene via pyrolysis and controlled chemical treatment [12]. The resulting graphene exhibits excellent mechanical and conductive properties, highlighting the potential of hardwood biomass as a viable renewable source for advanced carbon materials [25]. The use of Quercus ilex aligns with global trends toward environmentally responsible production of high-performance materials.

Coffee waste represents another innovative precursor, transforming organic residues into functional graphene with notable electrical and thermal conductivity [13]. Although typically more defect-rich compared to other biomass-derived graphene materials, coffee-derived graphene is advantageous for applications where higher surface reactivity or enhanced defect sites improve performance—such as in catalysis, adsorption, and electrochemical energy systems [26]. This conversion route also

contributes to sustainable waste management practices.

PMDS (Polymethylated Dimethyl Siloxane) and lignin—representing polymeric and plant-based precursors—have recently gained attention for producing graphene through chemical and thermal conversion pathways. Their structural characteristics contribute to graphene with high surface area, substantial mechanical strength, and superior conductivity, although often with higher defect densities compared to graphite-based graphene [14]. The integration of polymeric and lignin-rich biomass precursors expands the diversity of carbon sources available for advanced material fabrication, reinforcing the importance of sustainable alternatives.

Empty fruit bunch (EFB) biomass from palm oil production serves as another abundant and renewable precursor for graphene synthesis [15]. Its transformation into graphene through pyrolysis and chemical processing yields a material with high mechanical strength, strong electrical and thermal conductivity, and excellent structural adaptability. As one of the most significant agricultural wastes in palm-producing regions, EFB-derived graphene supports environmentally responsible industrial practices while offering high application potential in electronics, renewable energy technologies, and structural composites [27, 28].

Tea waste, originating from spent tea leaves, also demonstrates considerable promise for producing graphene via pyrolysis and chemical activation [16]. The resulting graphene exhibits strong mechanical properties, high conductivity, and broad application potential, further reinforcing the suitability of organic biomass as an alternative carbon feedstock [29]. This conversion process underscores the importance of integrating waste valorization with advanced material development.

Raman spectroscopy plays a central role in evaluating the structural characteristics of all biomass-derived graphene materials. The D-band (I_D) reflects structural defects or disorder, while the G-band (I_G) corresponds to the vibrational mode of sp^2 carbon networks in ordered graphitic structures [30]. The I_D/I_G ratio serves as a critical indicator of defect density, graphitization quality, and precursor suitability. Additional spectral features such as f_D and f_G provide insights into strain effects, heteroatom incorporation, and carbon network regularity. Collectively, Raman spectral analysis offers a detailed understanding of the structural behavior, conversion efficiency, and material quality of graphene synthesized from diverse biomass sources, making it an indispensable tool in advanced carbon material research [31].

CONCLUSION

The analysis of Raman spectroscopic data demonstrates that palm kernel shell–derived graphene exhibits I_D/I_G ratios ranging from 1.04 to 1.30, indicating a moderately disordered yet structurally competitive graphene quality. When compared with other precursors, such as commercial graphite—which displays an exceptionally low I_D/I_G value of 0.09 indicative of highly crystalline graphene—and coffee waste, which shows the highest defect density with an I_D/I_G ratio of 1.78, palm kernel shells offer a balanced compromise between material performance and production cost. Although precursors such as PMDS/lignin yield the highest I_D/I_G ratios (1.86), reflecting lower graphitic quality, palm kernel shells remain an attractive option due to their sustainability advantages, abundance, and potential to reduce industrial biomass waste. Overall, palm kernel shells represent a promising, environmentally responsible, and economically viable feedstock for the scalable production of graphene.

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