Point of Care Devices Engaging Green Graphene: An Eco-conscious and Sustainable Paradigm

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Abstract:

The healthcare landscape has experienced a profound and irreversible transformation, primarily driven by the emergence of nanomaterial assisted point-of-care (POC) devices. Inclusion of nanomaterials in POC devices have revolutionized healthcare by enabling rapid, on-site diagnostics with minimal infrastructure requirements. Among the materials poised to lead this technological revolution, green graphene emerges as a compelling contender. It possesses a unique combination of exceptional material properties and environmentally conscious attributes. These attributes include its substantial surface area, unparalleled electrical conductivity, and inherent biocompatibility. This article embarks on an exploration of POC devices incorporating green graphene. It meticulously dissects the intricacies of their design, performance characteristics, and diverse applications. Throughout the exposition, the transformative impact of green graphene on the advancement of POC diagnostics takes centre stage. It underscores the material's potential to drive sustainable and effective healthcare solutions, marking a significant milestone in the evolution of healthcare technology.

Keywords: Graphene; Point of Care (POC); Eco-Sustainable Nanomaterial; Green Diagnostics; Healthcare monitoring.

1. Graphene to Green Graphene: The Journey

Graphene, an atom-thick arrangement of carbon atoms forming a hexagonal lattice, stands as a testament to scientific marvel. Its structure, reminiscent of a honeycomb, grants it extraordinary properties, making it a frontrunner in material science. This two-dimensional wonder material boasts unparalleled strength, exceptional electrical conductivity, and remarkable flexibility, sparking a revolution in various industries, from electronics to medicine. Graphene synthesis methods encompass a diverse range of techniques (Fig 1), each offering unique pathways to harness this extraordinary two-dimensional material.

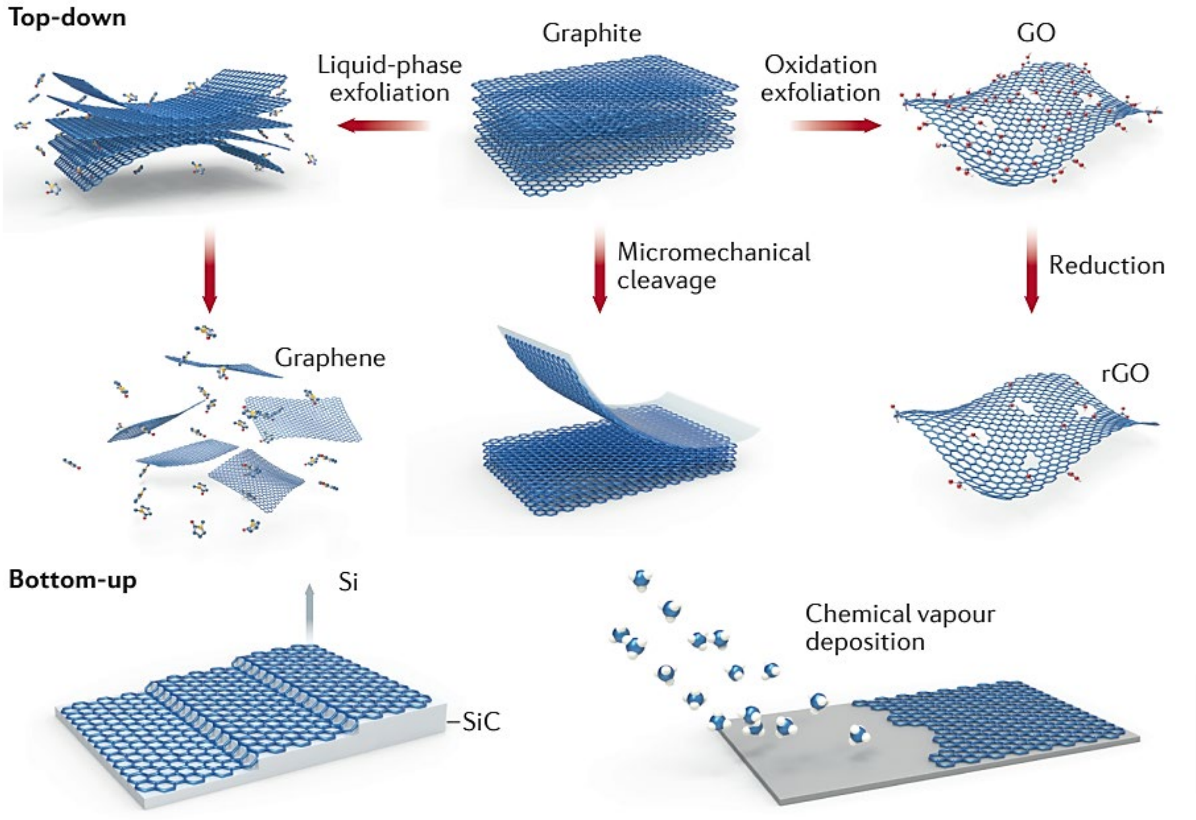

Fig 1: Graphene is produced via two main methods: top-down, which involves exfoliation or oxidation of graphite to create graphene, and bottom-up, where graphene is grown on materials like SiC or Cu using processes like epitaxial growth or chemical vapor deposition. (Reproduced from ref. 1 with permission from Springer Nature, copyright 2017)

Mechanical Exfoliation: This pioneering technique, although simple in concept, involves a meticulous process[2]. By repeatedly peeling graphite with adhesive tape, thin layers of graphene are isolated. This method initially showcased the remarkable properties of graphene due to its purity. However, its application is limited to research and small-scale experiments due to low yield and scalability issues[3]. Despite its limitations, it remains a fundamental technique for studying graphene's intrinsic properties.

Chemical Vapor Deposition (CVD): CVD has gained prominence for its potential to produce large-area graphene films[4]. This process occurs in a high-temperature furnace where a carbon-containing gas, like methane, decomposes on a metal substrate, typically copper. Carbon atoms then assemble into a graphene layer on the substrate. CVD offers greater control over the graphene layer's thickness and is suitable for industrial-scale production. However, challenges include optimizing growth conditions and choosing suitable substrates to ensure high-quality graphene films.

Liquid-Phase Exfoliation: This method involves breaking down graphite into graphene in a liquid medium, utilizing forces like sonication or shear forces[5]. By dispersing graphite in a solvent and applying energy, graphene nanoplatelets or dispersions are obtained. This technique has gained attention for its scalability and versatility, providing dispersed graphene suitable for various applications. However, achieving a high yield of monolayer graphene remains a challenge.

Oxidation-Reduction: The Hummers' method, an oxidative approach, involves treating graphite with strong oxidizing agents like sulfuric acid and potassium permanganate to produce graphite oxide[6]. Subsequent reduction yields reduced graphene oxide (rGO). This method is relatively simple and yields graphene oxide (GO), which, while not as pristine as graphene, exhibits notable properties and can be dispersed in solvents. However, the presence of oxygen-containing functional groups in rGO affects its electrical and mechanical properties compared to pristine graphene.

While these methods have significantly contributed to graphene research and application, the focus is gradually shifting towards sustainable synthesis methods. The aim is to reduce the environmental impact and reliance on resource-intensive processes, promoting eco-friendly and scalable approaches that maintain or enhance graphene's properties for a range of applications. While successful in producing graphene, these methods often relied on resource-intensive procedures, harsh chemicals, and high energy demands. This raised concerns about their ecological impact and sustainability, prompting a critical reassessment of synthesis approaches.

The quest for sustainability within graphene synthesis birthed a transformative shift towards eco-friendly and resource-efficient methods. This evolution signifies a departure from conventional routes and embraces sustainable synthesis methodologies. Emphasizing principles of green chemistry, these newer approaches aim to minimize chemical usage and energy consumption, ensuring a more environmentally benign production of graphene. Additionally, bio-inspired methods draw inspiration from nature's efficiency, seeking to replicate natural processes for sustainable graphene synthesis, termed as green graphene.

Green graphene, as implied by its nomenclature, encompasses a category of carbon-based nanomaterials distinguished by their eco-sustainable attributes. These materials exhibit the fundamental structural composition of graphene, comprising a singular layer of carbon atoms arranged within a hexagonal lattice. Nevertheless, the distinguishing feature that sets green graphene apart lies in the utilization of sustainable and environmentally conscientious methodologies throughout its synthesis process[7].

2. Green Graphene: Synthesis and Applicability in Eco-Sustainable Diagnostics

Traditional graphene production processes involve energy-intensive and chemically harsh methods, often relying on the use of hazardous chemicals and non-renewable resources. In contrast, green graphene is synthesized using eco-friendly approaches that prioritize sustainability and reduced environmental impact (Fig 2).

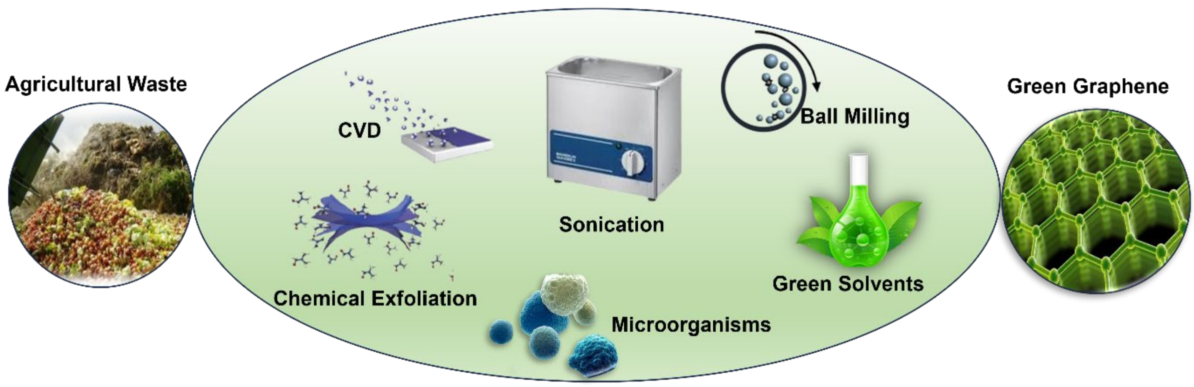

Fig 2: Processes involved in the production of green graphene.

Biomass Conversion: Biomass conversion for green graphene synthesis is an ecologically conscious methodology that harnesses renewable organic materials to produce graphene and related materials while minimizing environmental harm, representing a significant stride towards eco-sustainable nanomaterial manufacturing. The process begins with the meticulous selection of appropriate biomass sources[8], often including wood[9] (Fig 3), agricultural residues (such as rice husks[10], cornstalks[11], or sugarcane bagasse[12]), and algae[13]. These sources are preferred due to their renewability, abundance, and biodegradability. To extract the carbon-rich components necessary for graphene synthesis, biomass materials undergo pretreatment. This phase involves physical processes like milling or crushing, as well as chemical treatments like acid or alkali hydrolysis to break down complex organic structures. Following pretreatment, the biomass undergoes carbonization, wherein it's heated in an oxygen-limited environment, thermally decomposing to produce carbon-rich residues known as biochar or carbonized biomass[14], serving as graphene precursors. This carbonized biomass, or biochar, serves as the starting point for graphene synthesis, utilizing various methods such as CVD, liquid-phase exfoliation, or reduction of GO. In some instances, biochar undergoes further purification and exfoliation processes to yield top-quality graphene materials. Biomass conversion for green graphene synthesis inherently embraces eco-sustainability. It reduces dependence on non-renewable carbon sources, minimizes waste generation, and diminishes the environmental footprint typically associated with traditional graphene production methods, like CVD utilizing hydrocarbon gases[15]. An additional eco-friendly advantage lies in the biodegradability of residual biomass. Any unused or byproduct biomass naturally degrades, minimizing environmental impact and waste accumulation. Furthermore, utilizing biomass sources for green graphene synthesis contributes to carbon sequestration[16]. Carbon absorbed from the atmosphere during the biomass growth cycle remains sequestered within the graphene materials, reducing carbon emissions.

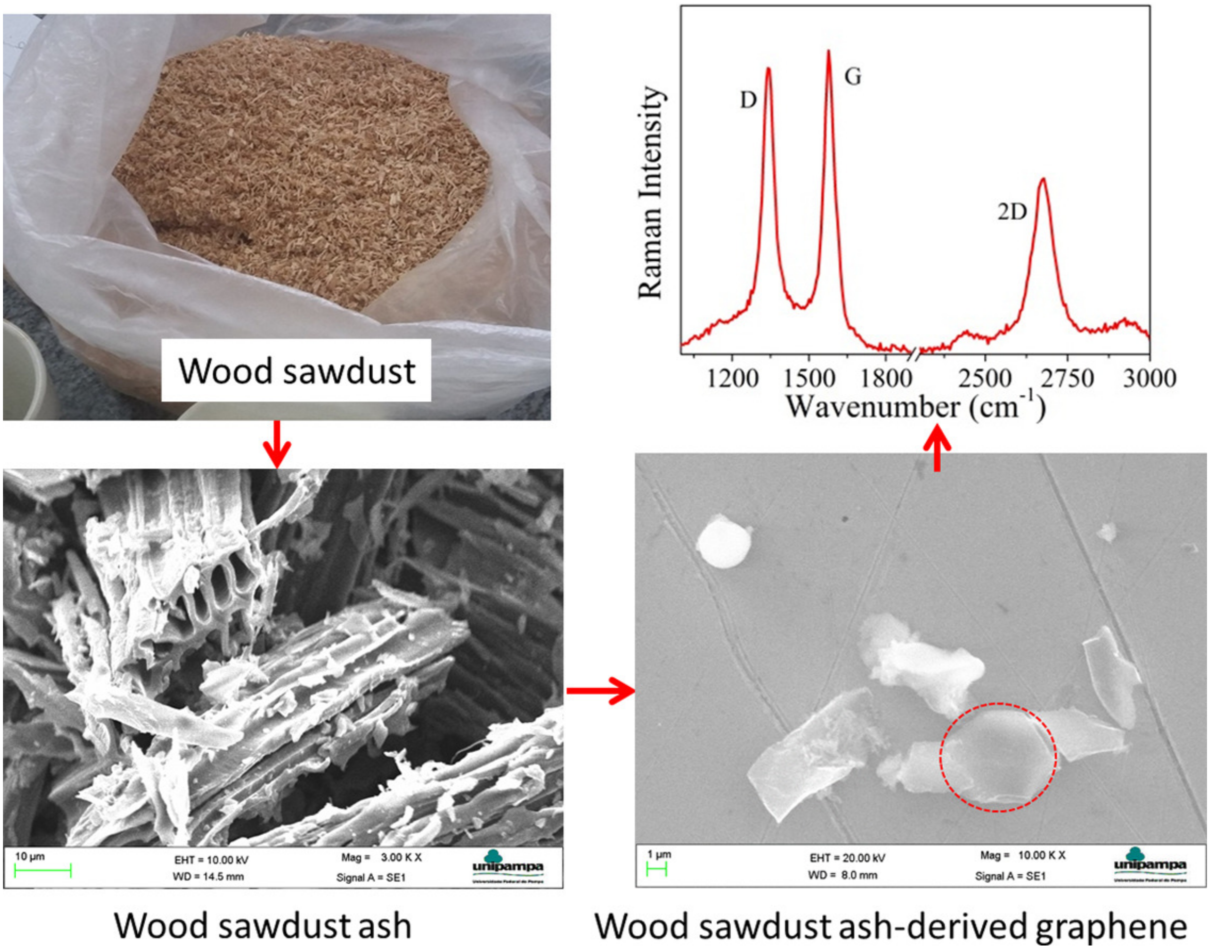

Fig 3: (From top left anticlockwise) Optical image of wood sawdust, SEM image of wood sawdust, SEM image of wood sawdust ash-derived graphene, Raman spectrum of wood sawdust ash-derived graphene. (Reproduced from ref. 9 with permission from Elsevier, copyright 2021)

***Green Solvents**:* Green solvents are integral to the eco-sustainable synthesis of green graphene and its related materials, playing a pivotal role in minimizing the environmental footprint of graphene production. Notable examples include water[17] (Fig 4), ethanol[18], isopropyl alcohol[19] and supercritical carbon dioxide ($scCO_2$)[20], all preferred for their ability to mitigate health hazards and reduce the release of volatile organic compounds (VOCs) into the atmosphere. Green solvents find application in various stages of green graphene synthesis. They are frequently employed in the reduction of GO to produce rGO, a critical step in restoring electrical conductivity to the material. Traditional reduction methods often rely on harsh chemicals, but green solvents like ascorbic acid[21] dissolved in water or ethylene glycol[22] provide a sustainable alternative, minimizing environmental harm. In the technique of liquid-phase exfoliation, used to create graphene nanoplatelets from bulk graphite or graphite oxide, green solvents such as terpineol[23] or eco-friendly surfactants like sodium dodecyl sulfate (SDS)[24] facilitate the exfoliation process. This reduces dependence on hazardous or non-renewable materials and enhances overall sustainability. Supercritical carbon dioxide ($scCO_2$) represents an eco-conscious choice for the exfoliation of graphite and graphene production. In its supercritical state, CO_2 effectively penetrates graphite layers, facilitating exfoliation without introducing environmental hazards. $scCO_2$ is non-toxic, non-flammable, and widely available, making it an environmentally responsible option for graphene production. The use of green solvents in graphene synthesis substantially reduces the generation of hazardous waste and the reliance on toxic chemicals, aligning with the principles of eco-sustainability.

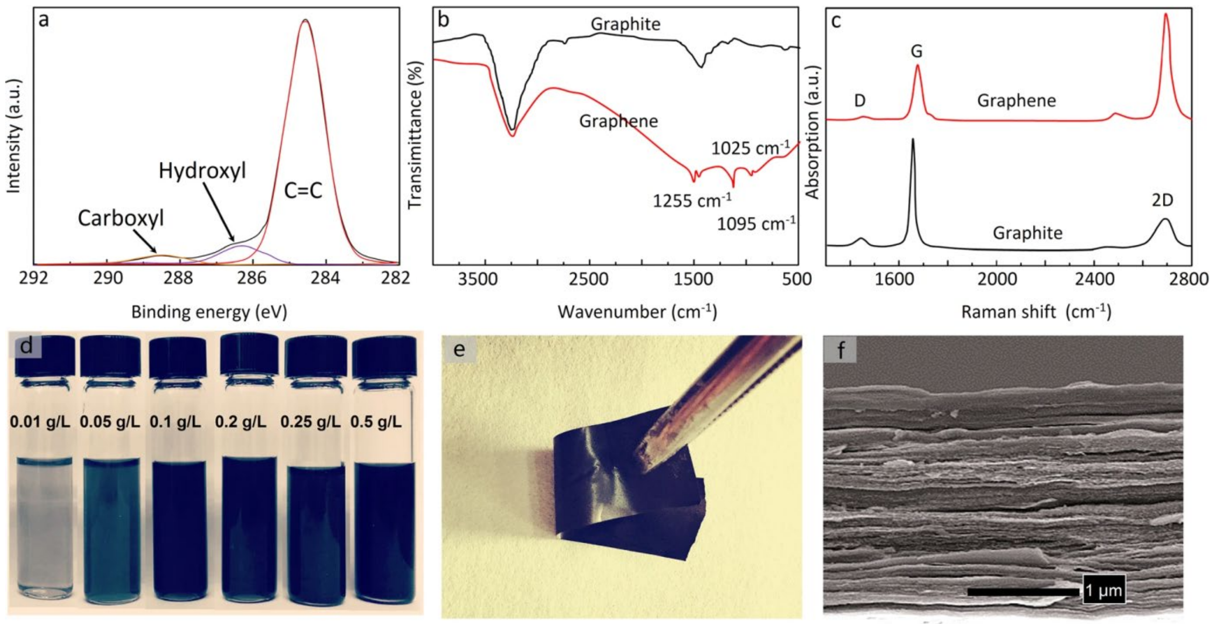

Fig 4: Analysis of the chemical compositions of graphene nanoplatelets involves various techniques: (a) X-ray Photoelectron Spectroscopy (XPS), (b) Fourier Transform Infrared Spectroscopy (FTIR), and (c) Raman spectroscopy. Additionally, (d) images of solutions containing dispersed graphene in deionized water after a month, (e) a photograph depicting a 3 µm thick graphene paper measuring 1 × 3 cm, and (f) a side-view scanning electron microscope (SEM) image illustrating a thick graphene paper are employed for comprehensive characterization. (Reproduced from ref. 17 with permission from Springer Nature, copyright 2018)

***Microbial Reduction**:* An innovative and eco-sustainable approach for the synthesis of green graphene and related materials is represented by microbial reduction[25]. The metabolic prowess of selected microorganisms, including bacteria like Shewanella[26] (Fig 5), Escherichia coli[27], Bacillus sphaericus[28] and Lactobacillus Plantarum[29], renowned for their capacity to reduce GO to rGO, is tapped into by this method. Initiation of the process involves the cultivation of these microorganisms under controlled conditions, where they are allowed to thrive in a growth medium containing essential nutrients, a carbon source, and GO as the substrate for reduction. During their growth phase, enzymes like cytochrome C and reductases, which play a pivotal role in catalyzing the reduction of oxygen-containing functional groups on the GO sheets, leading to the formation of rGO, are naturally produced by these microorganisms. Particular attractiveness is found in microbial reduction due to its inherent eco-sustainability[30]. The reliance on harsh and environmentally detrimental chemicals is drastically reduced, the generation of toxic waste products is minimized, and concerns related to health and safety, typically associated with traditional reduction methods, are alleviated. Furthermore, the resulting rGO exhibits biocompatibility, rendering it suitable for various biomedical applications. One of the remarkable features of microbial reduction is its controllability. The process can be fine-tuned by adjusting factors such as pH, temperature, and the specific microorganism strain employed, allowing for the tailoring of rGO properties to meet specific application requirements. This versatility extends to various forms of GO, including GO nanosheets and films, making microbial reduction a versatile and environmentally friendly method for the production of green graphene.

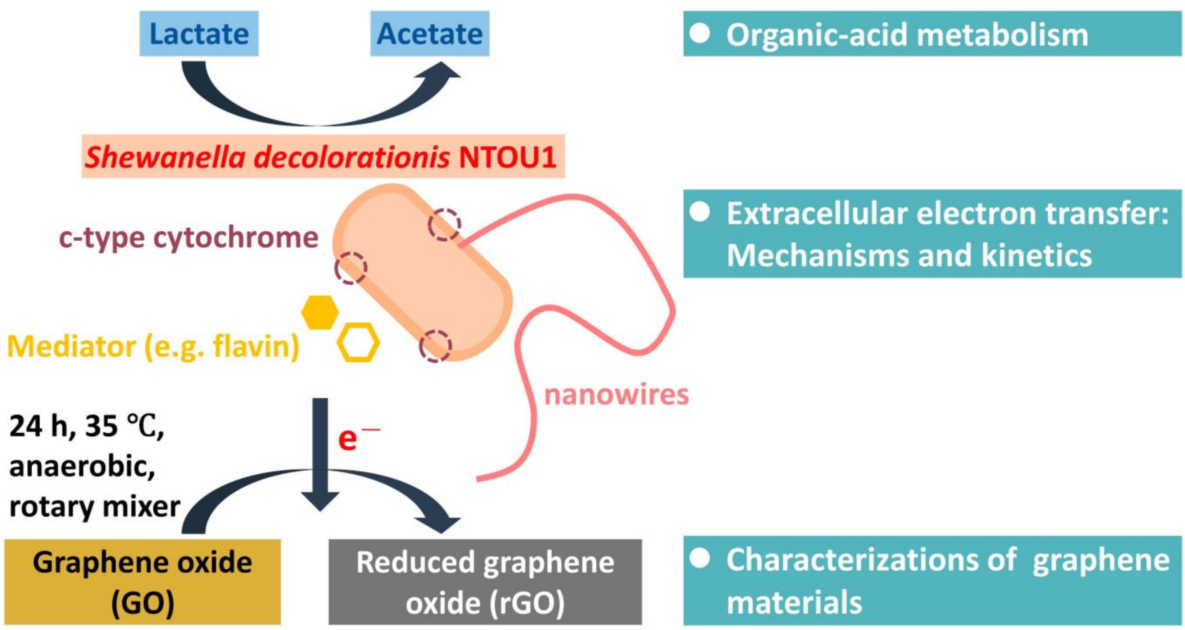

Fig 5: Mechanisms and Kinetics of Extracellular Electron Transfer in Shewanella decolorationis NTOU1 Reducing Graphene Oxide through Lactate Metabolism. (Reproduced from ref. 31 with permission from MDPI, copyright 2023)

Applicability in Eco-Sustainable Diagnostics: Green graphene materials align with eco-sustainable diagnostics principles in several ways. Firstly, their renewability is a standout feature as they can be sourced from renewable feedstocks[32], reducing reliance on non-renewable resources and contributing to sustainable resource management. Additionally, some green graphene materials are inherently biodegradable[33], ensuring minimal environmental impact at the end of their lifecycle, a critical factor for eco-conscious diagnostic applications. Eco-friendly synthesis methods used in their production further reduce environmental impact by minimizing the use of hazardous chemicals and energy-intensive processes. Furthermore, green graphene materials are often biocompatible[34], making them ideal for biomedical applications and minimizing potential harm to living organisms during diagnostics. These materials can be synthesized using energy-efficient methods[35], contributing to more sustainable production processes and conserving energy resources. Lastly, prioritizing cost-effective and eco-friendly synthesis approaches makes green graphene materials more accessible for widespread use in diagnostics, especially in resource-limited settings, thus promoting equitable access to advanced diagnostic technologies while supporting environmental sustainability (Fig 6).

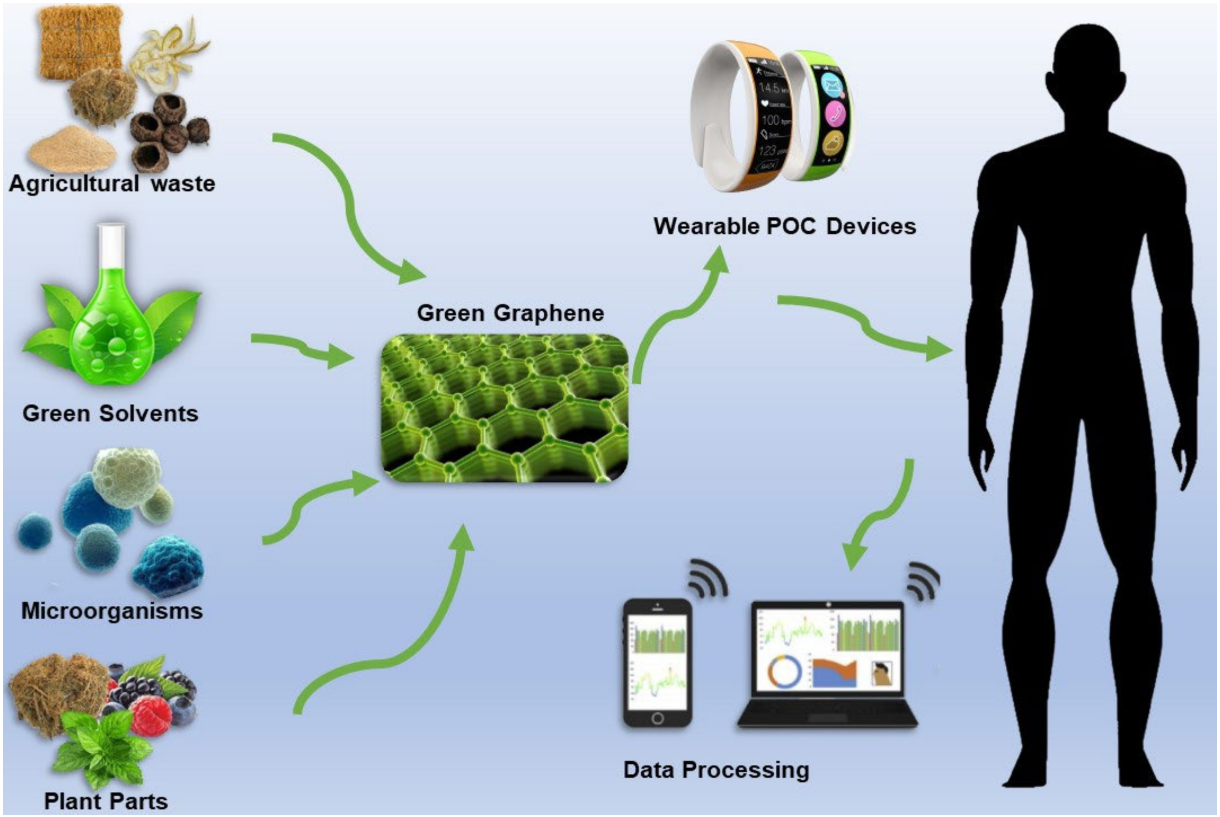

Fig 6: Designing a blueprint for incorporating eco-friendly graphene in point-of-care devices to boost efficiency and promote environmental solutions.

3. Significance of Green Graphene in POC Devices

In modern healthcare, a transformative force is represented by POC devices[36], frequently referred to as bedside or near-patient testing devices. The landscape of medical diagnostics has been reshaped by these innovative instruments through the offering of rapid and convenient solutions right at the patient's side or in close proximity to their care environment. Not only in their convenience but also in their capacity to play a pivotal role in the early detection of diseases[37], continuous monitoring of health parameters, and the timely initiation of treatment interventions, lies the significance of POC devices. This, in turn, is associated with a profound impact on patient outcomes, promoting faster recovery, more effective management of pandemic conditions[38], and even the potential for saving lives.

As relentless progress continues within the healthcare sector, two critical considerations have emerged as central to its evolution: environmental conservation[39] and equitable healthcare accessibility[40]. In the face of growing environmental concerns and the imperative to make advanced healthcare technologies available to all, regardless of geographical or economic disparities, the need for eco-sustainable POC devices has become increasingly apparent. It is within this context that the attention of researchers, healthcare professionals, and innovators has been captured by green graphene, an environmentally friendly nanomaterial. The pressing concerns of environmental conservation and advancing the field of POC diagnostics are addressed by the unique attributes of green graphene.

By virtue of its environmental friendliness, green graphene stands out, characterized by its sustainable synthesis methods[41]. Unlike certain conventional materials used in medical technologies, processes that are less resource-intensive and less harmful to the environment can be employed for the production of green graphene. The global imperative to mitigate the ecological footprint of healthcare technologies is aligned with this sustainable ethos[42].

The appeal of green graphene extends beyond its eco-conscious production methods. This nanomaterial, encompassing graphene, GO, and rGO, boasts a host of distinctive physical and chemical properties that can be skilfully harnessed to elevate the sensitivity, specificity, and overall environmental sustainability of diagnostic assays[43].

The proactive response to the growing emphasis on environmental sustainability within healthcare is signified by the incorporation of green graphene into POC devices[44]. Through the harnessing of eco-friendly nanomaterials and the adoption of sustainable manufacturing practices, the ecological impact of the healthcare industry can be substantially reduced. Additionally, the utilization of green graphene-based components may pave the way for the creation of disposable, biodegradable, or recyclable elements, further minimizing waste generation within healthcare settings[45].

In essence, an exhilarating frontier in the realm of eco-sustainable diagnostics is represented by the integration of green graphene into POC devices. This convergence of cutting-edge technology and environmental stewardship has the potential to redefine the healthcare landscape by delivering advanced diagnostics while reducing the ecological footprint of medical practice[46].

4. POC Devices Engaging Green Graphene for Healthcare Applications

Green graphene-powered POC devices stand as a beacon in healthcare, fusing precision with sustainability to revolutionize diagnostics, ensuring swift and eco-conscious patient care while advancing environmental responsibility in medical technology. This discourse particularly focuses primarily on the past five-year timeframe, emphasizing graphene's effectiveness within POC devices.

Diabetes Monitoring**:** Diabetes monitoring through green graphene POC devices marks a ground-breaking stride in healthcare. These devices, crafted with eco-friendly graphene, revolutionize glucose monitoring. Their ultra-sensitive and rapid detection capabilities offer real-time data, empowering individuals to manage diabetes efficiently.

Significant promise was shown in the utilization of lemon peel phytoextract as an eco-friendly candidate for the environmentally conscious reduction of GO. Following this, a green synthesis method for producing rGO was proposed by Gijare et al.[47], employing lemon peel extract rich in vitamin C. This rGO was subsequently utilized as an electrochemical nonenzymatic glucose sensor for human serum analysis. For the preparation of GO, an improved modification of the Hummer's method was chosen, ensuring a more efficient and environmentally friendly process. Remarkable sensitivity was exhibited by the resulting glucose sensor, with a measurement of 1402 μAcm^{-2} mM^{-1}, along with a correlation coefficient of 0.9887 and an impressive limit of detection (LOD) of 0.011 μM. Additionally, exceptional accuracy was displayed when glucose in human blood serum was detected by the sensor, with a relative standard deviation of only 1.99% in 5s. Importantly, the measurements obtained were closely aligned with those from professional glucose sensors utilized in medical settings, showcasing the reliability of the proposed biosensor.

Later on, Gijare et al.[48] explored rGO/ Titanium dioxide (TiO_2) electrodes for glucose sensing, with emphasis placed on their stability, sensitivity, and reproducibility (Fig 7). An eco-friendly method using citrus limetta peel waste to produce rGO was introduced, and the properties of the composite were analyzed through microwave heating. The sensor, which had been modified with a fluorine-tin oxide substrate, demonstrated high sensitivity (1425 $\mu A/mM\ cm^2$) within a glucose range of 0.1 to 12 mM, exhibiting excellent stability, repeatability (5-second response time), and a low detection limit (0.32 μM).

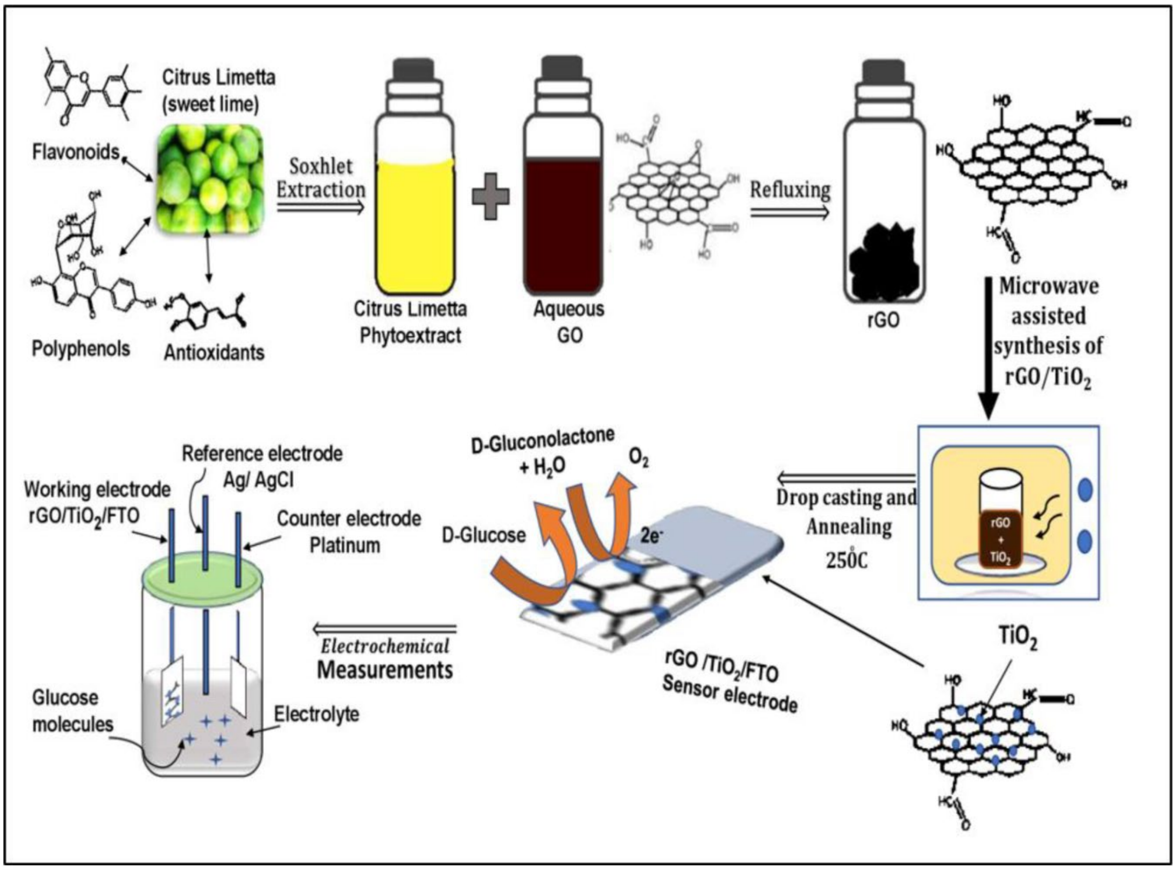

Fig 7: Mechanism of green reduction of GO and rGO/TiO_2/ Fluorine-doped Tin Oxide (FTO) for glucose sensing application. (Reproduced from ref. 48 with permission from MDPI, copyright 2023)

Hwang et al.[49] introduced an innovative one-pot synthesis approach for the production of reduced-graphene oxide quantum dots (rGOQDs) in a perfluorotributylamine (PFTBA) solution. This method not only eliminated the requirement for toxic materials but also prevented the formation of undesirable functional groups such as epoxy, carbonyl, and carboxyl. The PFTBA solution, characterized by three butyl fluoride groups linked to an amine center, efficiently decomposed rGO precursors at around 160 °C, yielding rGOQDs of exceptional purity. Notably, as the solution temperature was increased from 160 °C to 190 °C, the photoluminescence (PL) emission peak was observed to shift from 489.3 nm to 460.8 nm, attributed to bandgap enhancement. The resulting sample demonstrated remarkable long-term photostability, with intensity maintained without decay over a span of 30 days, thus rendering it highly suitable for optical device applications. Moreover, when combined with glucose oxidase (GOx), the PL spectra of the rGOQDs-solution underwent a colour change from blue to green with impressive sensitivity of 3.869 deg/mM within the glucose concentration range of 0 to 2 millimoles, underscoring the potential utility of rGOQDs in colorimetric biosensors, including those designed for portable smartphone integration.

Human Motion Pressure Monitoring: Human motion pressure monitoring through green graphene POC devices marks an innovative stride in healthcare. With its ultra-sensitive capabilities, this technology harnesses the power of green graphene, offering a non-invasive and efficient means to track bodily movements and pressure dynamics.

In the Internet-of-Things (IoT) era, there is an increasing demand for flexible sensors in intelligent systems. However, reliance on petrochemical materials and the utilization of toxic chemicals in manufacturing by most of these sensors posed potential health risks. A sustainable method for crafting pressure sensors using bacteria cellulose and caffeic acid-reduced rGO composite aerogel was presented by Wei et al.[50]. Enabled by its three dimensional (3D) hierarchical porous structure, the aerogel facilitated exceptional sensor performance, featuring high sensitivity (13.89 kPa^{-1}), an incredibly low detection limit of 47.2 Pa, and with rapid response time of 120 ms. This allowed for the precise detection of subtle strain and monitoring of human movements (Fig 8). Remarkably, outstanding reproducibility was demonstrated by the aerogel over 1000 cycles of pressure loading and unloading. Consequently, the potential for utilizing natural resources in crafting flexible functional materials was highlighted within the realm of flexible electronics.

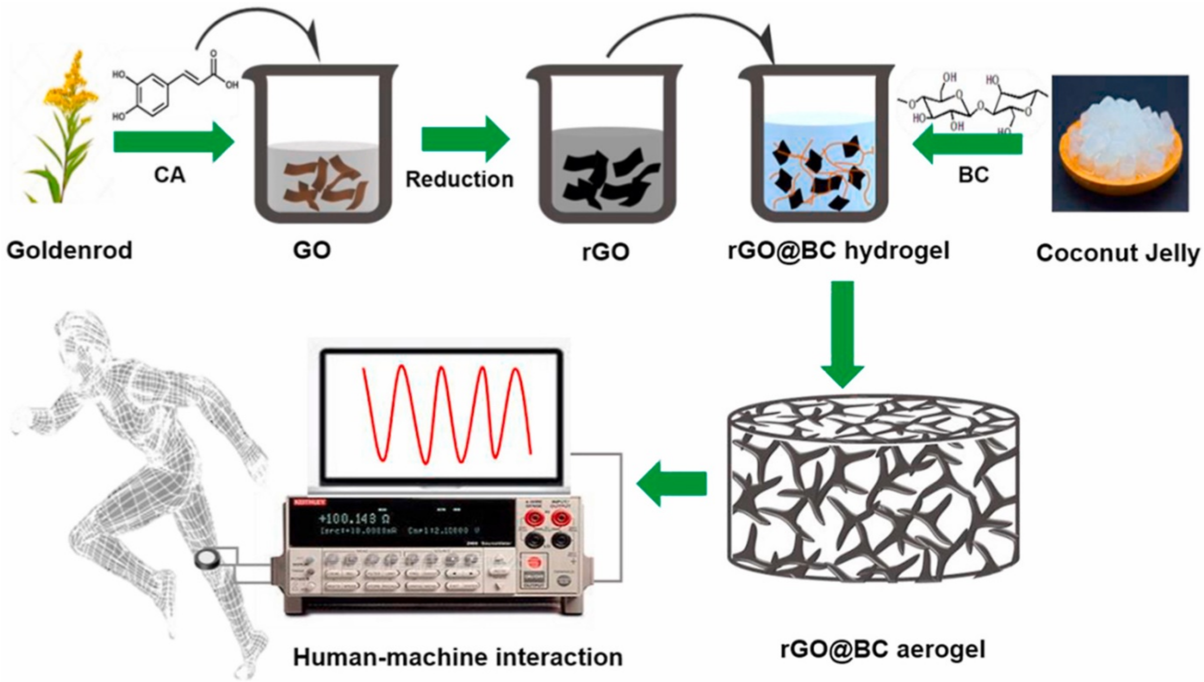

Fig 8: Steps involved in creating environmentally friendly graphene/biomass aerogels with high sensitivity and flexibility for pressure sensing applications. (Reproduced from ref. 50 with permission from Elsevier, copyright 2021)

Flexible piezoresistive sensors have been acknowledged for their versatile healthcare applications. However, the fabrication processes for these sensors were commonly recognized as being costly, complex, and environmentally detrimental. Li et al.[51] employed L-cystine as the green reductant and templating agent to produce 3D rGO aerogel (Fig 9). Polyvinyl chloride tape was used as substrates to encapsulate the aerogel, enabling the creation of the piezoresistive sensor. The sensor, which demonstrated good linearity between resistance and logarithmic pressure values across a wide range from 170.4 kPa to 2.4 MPa, effectively monitored wrist pulse and human motion. Sensors manufactured through this straightforward and cost-effective method exhibited significant potential for electronic skin applications.

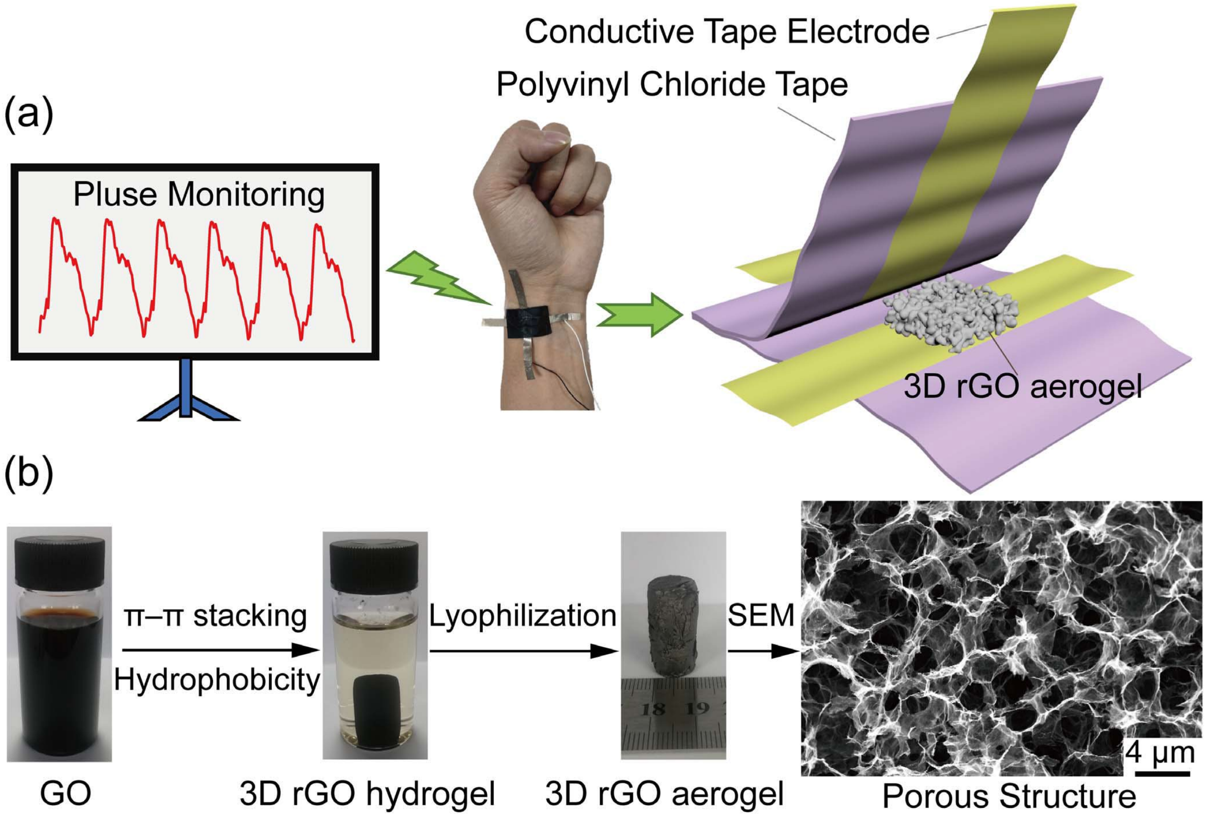

Fig 9. (a) Schematic diagram of piezoresistive pressure sensor based on 3D rGO aerogel. (b) The photograph of GO, 3D rGO hydrogel/aerogel, and the scanning electron microscopy (SEM) of aerogel. (Reproduced from ref. 51 with permission from IEEE, copyright 2021)

Water and Food Quality Monitoring: Monitoring water and food quality using green graphene POC devices marks a revolutionary leap in ensuring safety. These devices, leveraging the incredible properties of green graphene, offer rapid and precise detection of contaminants. With their high sensitivity, they detect pollutants or pathogens swiftly, enabling proactive measures.

Considerable research attention was attracted to graphene quantum dots (GQDs) due to their favorable biocompatibility, minimal toxicity, remarkable fluorescence, and intriguing physicochemical traits. However, persistent fundamental challenges, notably acidic contamination and high production costs, hindered their commercial viability. In this investigation, Abbas et al.[8] introduced an environmentally friendly single-step method for GQD synthesis, utilizing biomass waste as a green precursor and the relatively eco-friendly solvent 'ethanol'. This approach effectively addressed issues related to strong acid contaminants and the elevated costs associated with expensive precursors. The findings indicated that the synthesized GQDs ranged in size from 0.5 to 4 nm and exhibited a thickness of 1 to 3 layers of graphene. These GQDs displayed substantial surface grafting and exceptional optical characteristics, boasting a high quantum yield of 21%. Leveraging these unique optical properties, the GQDs were utilized as a fluorescence probe for the detection of ferric ions (Fe^{3+}). A precise and selective sensor was developed, demonstrating a detection limit as low as 0.5 μM. The significance of employing a relatively eco-friendly process and cost-effective biomass precursor for producing high-quality GQDs was underscored by this study, setting a promising trajectory for their utilization in many applications especially water quality monitoring.

The exploration of various natural substances has been prompted by the endeavour to develop a straightforward, cost-efficient, and eco-friendly approach for synthesizing rGO. Equally crucial is the vigilant monitoring of sunset yellow (SY) levels in food owing to its potential adverse effects. In their investigation, the utilization of tea extract as both a reducing agent and a stabilizer in the synthesis of rGO was explored by Vatandost et al.[52]. The detection of SY was enabled through the utilization of the rGO-modified carbon paste electrode (rGO/CPE) as an exquisitely sensitive electrochemical sensor. A pronounced enhancement effect on the electrochemical oxidation of SY was demonstrated by the substantial surface area of the rGO/CPE. A discernible linear range spanning from 0.05 to 10 μM, along with a remarkably low detection limit of 27 nM, was achieved under optimized parameters. Satisfactory outcomes in quantifying SY levels in food products were obtained by employing this proposed sensor, aligning well with the findings obtained through Ultraviolet-visible spectroscopy.

The green ultrasonic microwave-assisted method was employed by Taşaltın et al.[53] to prepare rGO, which was subsequently investigated for its application in a non-enzymatic electrochemical sensor to detect the synthetic fungicide propamocarb (PM) pesticide. A rapid response time of within 1 minute was displayed by the rGO-based sensor, which boasted a low detection limit of 0.6 μM. Furthermore, propamocarb pesticide levels in real cucumber samples were effectively detected by this sensor, demonstrating high sensitivity within the concentration range of 1 to 5 μM in a 1-minute cycle. Notably high specificity towards propamocarb pesticide was observed, indicating strong selectivity. The fabricated non-enzymatic electrochemical sensor exhibited notable characteristics, including high sensitivity, selectivity, reproducibility, and a swift response time.

Toxic Gas Monitoring: Green graphene-based POC devices offer a revolutionary approach to toxic gas monitoring. These devices harness the power of eco-friendly graphene to detect and measure harmful gases in real-time. Their portability and sensitivity make them invaluable tools in safeguarding environments and human health.

Sharma et al.[54] presented a green, rapid, and scalable method for synthesizing rGO utilizing an environmentally friendly reducing agent, l-glutathione/L-Glu. The objective was to assess the viability of rGO for CO & NO_2 gas sensing. L-Glu-rGO displayed a higher sp^2 carbon hybridization, 42%, compared to GO, 29%. The findings suggested that L-Glu-rGO demonstrated a notable relative response to both gases, 10 ppm of NO_2 and CO, at 150 °C. Furthermore, L-Glu-rGO exhibited a shorter response time, ∼10.61 s for NO_2 and ∼5.05 s for CO, compared to GO, ∼16.64 s for NO_2 and ∼11.92 s for CO respectively, at 150 °C, indicating the potential utility of L-Glu-rGO in gas sensing applications.

A comparative investigation between green (L-Ascorbic acid) and chemically reduced GO using hydrazine hydrate for NO_2 chemiresistive gas sensors was initiated by Rani et al.[55]. The process of reducing GO involved the elimination of oxygen-containing functional groups to produce highly reduced GO, exhibiting significant surface area and exceptional adsorption capacity, establishing its exceptional efficiency for gas sensing applications. rGO reduced with hydrazine hydrate (rGOH) displayed 80% sensitivity, accompanied by a shorter response time of 4s and recovery time of 7s compared to the green reductant L-AA (rGOA). Although exhibiting a 10% lower gas sensing performance than rGOH, rGOA maintained its viability for gas sensing applications owing to its economic feasibility and environmentally safe preparation method.

Graphene sheets with reduced defects dispersed with α-Fe_2O_3 were prepared by Haridas et al.[19] using a green solvent mixture for graphite exfoliation, followed by hydrothermal treatment with an iron precursor. The robust interaction between α-Fe_2O_3 and graphene was highlighted in characterization studies, emphasizing the reduced defects in the graphene sheets. Exceptional chemiresistive sensing properties tailored specifically for NH_3 gas, a hazardous industrial pollutant, were exhibited by the α-Fe_2O_3/graphene nanocomposite. At 250 °C, high sensor response, selectivity, and repeatability concerning NH_3 gas were showcased by the nanohybrid. Its sensor response remained linear within the 10 to 50 ppm range, displaying a regression coefficient of 0.95.

The prior discussion of POC devices based on green graphene for healthcare related applications is summarized in Table 1.

Table 1. Parameters of green graphene-based POC devices for healthcare applications.

Form of Graphene	**Green Method Used**	**Sensor Type**	**Sample Type**	**Target**	**LOD**	**Detection Range**	**Response Time**	**Use**	**Ref**
rGO	Lemon peel extract used for rGO synthesis	Electrochemical	Serum	Glucose	0.011 µM	0.1 to 10 mM	5s	Diabetes monitoring	47
rGO	Citrus limetta peel waste used for rGO synthesis	Electrochemical	Serum	Glucose	0.32 µM	0.1 to 12 mM	5s	Diabetes monitoring	48
rGOQDs	rGOQDs synthesized by avoiding the use of toxic materials and preventing the generation	Colorimetric	Solution	Glucose	3.869 deg/mM	NA	NA	Diabetes monitoring	49

	of undesirable functional groups								
rGO	Caffeic acid used for rGO synthesis	Electrical	NA	Various human physical motions	47.2 Pa	NA	120 ms	Pressure sensor	50
rGO	L-cysteine used for rGO synthesis	Electrical	NA	Various human physical motions	170.4 kPa	170.4 kPa to 2.4 MPa	NA	Pressure sensor	51
GQD	Biomass waste used for GQD synthesis	Optical	Water	Ferric ions	0.5 µM	NA	NA	Water quality monitoring	8
rGO	Green tea extract used for rGO synthesis	Electrochemical	Food	Sunset yellow	27 nM	0.05 to 10 µM	NA	Food quality monitoring	52
rGO	Green ultrasonic microwave assisted method used for rGO synthesis	Electrochemical	Food	Fungicide Propamocarb in Cucumber	0.6 µM	1 to 5 µM	1 min	Food quality monitoring	53
rGO	Environmentally friendly	Electrical	Gas	NO_2 and CO	10 ppm	NA	~10.61 s for NO_2 a	Toxic gas detecti	54

	reducing agent, l-glutathione /L-Glu used for rGO synthesis						nd ~5.05 s for CO	on	
rGO	L-ascorbic acid used for rGO synthesis	Electrical	Gas	NO_2	10 ppm	2 to 50 ppm	4s	Toxic gas detection	[55]
Graphene	Green solvent mixture (especially Isopropyl alcohol) used for graphene synthesis	Electrical	Gas	NH_3	10 ppm	10 to 50 ppm	152 min	Toxic gas detection	[19]

The diverse applications of POC devices with green graphene highlight their versatility and potential to advance healthcare, and environmental monitoring (Fig 10). These devices provide valuable tools for addressing critical challenges and improving our understanding of complex biological and environmental systems.

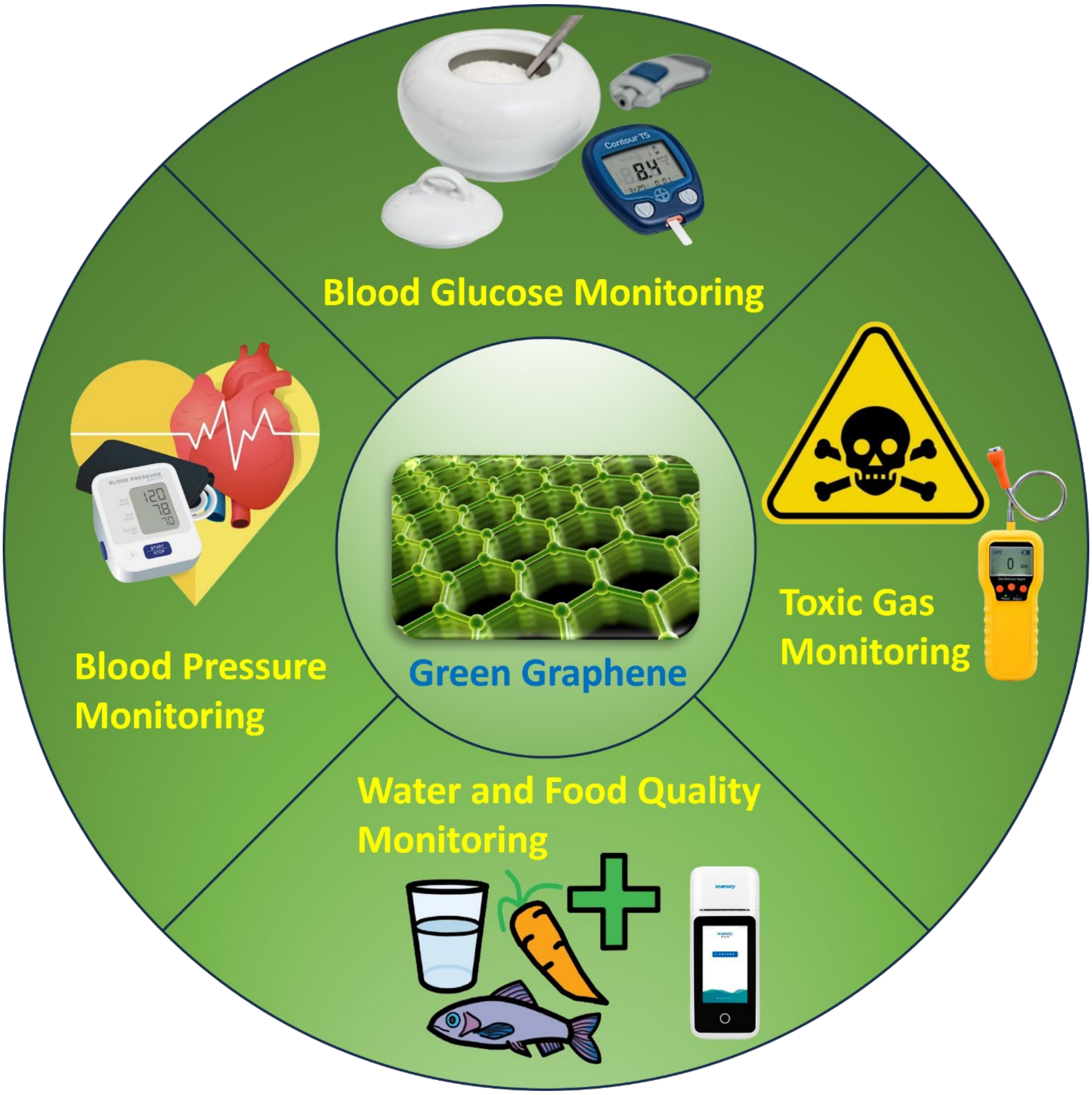

Fig 10: An illustration scheme to summarize the applications of green graphene in various POC devices.

5. Challenges and Future Directions

In the domain of POC devices with green graphene, numerous challenges and exciting future directions shape the landscape of eco-sustainable diagnostics. One of the central challenges lies in realizing the full potential of remote healthcare and telemedicine integration[56]. While POC devices equipped with green graphene offer the promise of accessible and reliable diagnostic tools for home-based monitoring, telemedicine consultations, and fieldwork applications, achieving seamless connectivity and robust data security remains an ongoing hurdle. The need to ensure that patient data is protected during transmission and storage is crucial to building trust in these remote healthcare solutions. Additionally, optimizing the user experience for both patients and healthcare professionals in telemedicine settings requires ongoing innovation and refinement.

Another significant challenge revolves around standardization and quality control[57]. To gain widespread acceptance and trust among healthcare providers and regulatory agencies, it is imperative to establish standardized testing protocols, quality assurance measures, and performance benchmarks for green graphene-based diagnostics. This process involves rigorous testing and validation to ensure that these devices consistently deliver accurate results. Streamlining these standards across different regions and healthcare systems is essential for the global adoption of eco-sustainable diagnostics.

Green graphene, while offering immense potential in various fields, presents concerns regarding toxicity across multiple fronts[58]. Inhalation of green graphene nanoparticles can lead to respiratory issues, skin exposure may disrupt barrier function and induce inflammation, and genotoxic effects have been observed, raising concerns about DNA damage. Additionally, its release into the environment poses ecological risks, and questions persist about its biocompatibility and biodegradability in biomedical applications. Understanding and mitigating these diverse toxicity concerns require comprehensive research efforts to ensure the safe development and utilization of green graphene-based materials.

At this juncture, it is imperative to undertake a structured and methodical comparison of graphene and green graphene, considering their diverse attributes (Table 2). This comparative analysis plays a pivotal role in informing decision-making processes concerning the selection and utilization of either graphene or green graphene in specific applications.

Table 2: Comparison of Key Attributes: Graphene vs. Green Graphene.

Attribute	Graphene	Green Graphene
Strength	Exceptionally strong	Varies, may not match conventional graphene
Conductivity	Highly conductive (electricity and heat)	Variable, may have lower conductivity
Flexibility	Highly flexible, suitable for various applications	Flexible, adaptable to some applications
Transparency	Transparent	Transparent
Weight	Very lightweight	Very lightweight
Production Cost	Relatively expensive	May be higher due to development costs
Environmental Impact	Energy-intensive production, use of harsh chemicals	Environmentally friendly production methods
Biodegradability	Generally, not biodegradable	Some forms are biodegradable
Market Acceptance	Widely accepted in various industries	Growing interest, but may face adoption hurdles
Performance	High performance in terms of conductivity and strength	Performance may vary, not always on par with conventional graphene

Green graphene, a sustainable alternative to traditional materials in POC devices, offers distinct advantages over conventional options. Compared to silicon, which is commonly used in POC devices, green graphene presents superior flexibility, enabling the development of more portable and wearable diagnostic tools. Additionally, green graphene exhibits higher electrical conductivity than traditional polymers like polydimethylsiloxane (PDMS), enhancing the sensitivity and accuracy of sensing elements in POC devices. Moreover, when compared to metal electrodes such as gold or platinum, green graphene demonstrates comparable conductivity[59] while being more cost-effective and environmentally friendly. Its biocompatibility and potential for biodegradability also surpass those of certain traditional materials, making it suitable for applications involving direct contact with biological samples. Furthermore, green graphene's transparent and lightweight properties offer advantages over traditional materials in optical and wearable POC devices, improving user experience and portability. Overall, the adoption of green graphene in POC devices represents a significant advancement toward sustainable and high-performance diagnostics, surpassing the capabilities of many traditional materials in terms of flexibility, conductivity, biocompatibility, and environmental impact.

Furthermore, navigating the regulatory approval and certification processes for innovative devices can be complex and time-consuming[60]. Manufacturers and researchers must navigate regulatory pathways to ensure that devices meet safety and efficacy standards. Simplifying and expediting these regulatory approval processes for sustainable and green technologies can significantly accelerate their deployment and impact.

To propel eco-sustainable diagnostics into the future, efforts should be concentrated on cost reduction and affordability[61]. This entails innovations in production techniques, materials sourcing, and supply chain management to make POC devices more cost-effective, especially in resource-limited settings. Comprehensive education and training programs are essential to ensure that healthcare providers, technicians, and end-users are proficient in operating these devices effectively. User-friendly interfaces and robust training initiatives can maximize the impact of these technologies and empower users to make informed healthcare decisions.

Conducting thorough environmental impact assessments[62] is vital to understanding the complete lifecycle environmental footprint of POC devices with green graphene. These assessments should consider factors such as material disposal, energy consumption, and manufacturing processes to identify opportunities for further eco-sustainability improvements. By addressing these environmental concerns, we can ensure that eco-sustainable diagnostics genuinely contribute to reducing the ecological footprint of healthcare.

Global accessibility and equity in healthcare diagnostics should be prioritized[63]. Efforts should be made to ensure that eco-sustainable POC devices with green graphene are not only technologically advanced but also accessible and affordable on a global scale. Addressing healthcare disparities and promoting equitable access to diagnostics are ethical imperatives that require collaborative efforts from governments, organizations, and healthcare providers worldwide.

Interdisciplinary collaboration is fundamental to driving innovation in eco-sustainable diagnostics[64]. Researchers, engineers, healthcare professionals, environmental scientists, and policymakers must work together to develop holistic solutions that address complex healthcare and environmental challenges. By combining their expertise, they can create devices that are not only effective but also environmentally responsible.

Continued research into emerging green graphene materials and their unique properties is critical. Investigating the biocompatibility, stability, and performance characteristics of these materials can unlock new possibilities for eco-sustainable diagnostics. Finally, public awareness and advocacy efforts are essential to raise awareness about the benefits of eco-sustainable diagnostics and green graphene materials. Advocacy can drive policy changes, funding allocation, and support for research and development in this field, ultimately contributing to a more sustainable and responsible healthcare ecosystem.

Thus, while POC devices with green graphene offer immense promise for eco-sustainable diagnostics[65], addressing challenges related to remote healthcare integration, standardization, regulatory approval, affordability, and environmental impact is essential. The future of these technologies lies in interdisciplinary collaboration, ongoing research into emerging materials, and global efforts to ensure equitable access to eco-sustainable diagnostics. As these challenges are addressed and innovations continue to emerge, we can look forward to a future where healthcare is not only effective but also environmentally conscious and accessible to all.

6. Conclusions

Eco-sustainable diagnostics represent a promising paradigm in healthcare, environmental monitoring, and scientific research. POC devices with green graphene materials offer eco-friendly solutions that align with principles of sustainability, affordability, and accessibility. These devices are characterized by their sensitivity, specificity, rapidity, portability, and cost-effectiveness, making them invaluable tools in diverse applications. As eco-sustainable diagnostics continue to evolve, researchers, manufacturers, healthcare providers, and policymakers must work collaboratively to overcome challenges and seize opportunities for innovation and improvement. By embracing green graphene materials, integrating advanced technologies, and upholding ethical principles, the field of eco-sustainable diagnostics can contribute to a healthier, more sustainable future for all.

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