Innovative Atmospheric Plasma Jets for Advanced Nanomaterial Processing

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Abstract: This study presents a comprehensive exploration of atmospheric pressure plasma jets (APPJs) as an innovative method for synthesizing and modifying nanomaterials, offering a versatile and efficient approach to tailoring their properties and functionalities. Unlike traditional low-pressure plasma techniques, APPJs operate at ambient conditions, providing significant advantages in scalability, cost-effectiveness, and environmental sustainability. This review delves into the recent advancements in APPJ technology, including the development of microfluidic configurations that enhance plasma generation and control, leading to improved efficiency, power, and user accessibility. These advancements have opened new possibilities in various fields, such as the development of antimicrobial coatings, advanced drug delivery systems, and high-performance solar cells. The ability of APPJs to facilitate precise surface engineering and targeted material deposition positions them as a transformative technology in nanomaterial processing. Despite their potential, challenges such as scalability and environmental impact must be addressed to realize widespread adoption. This study underscores the promise of APPJs in driving future industrial applications and highlights the need for continued innovation to overcome current limitations and unlock their full potential across multiple sectors.

Keywords: Atmospheric pressure plasma jets, Tailored Functionalities, Sustainable Processing, Advanced Industrial Uses.

1. INTRODUCTION

Nanomaterials, defined by their sub-100-nanometer dimensions, possess unique properties absent in bulk materials, which translates into superior performance [1] and innovative functionalities across various sectors such as electronics [2-4], healthcare [5-7], and environmental sustainability [8-10]. As research progresses, nanomaterials continue to reveal their transformative potentiall [11-13], influencing scientific and technological advancements [14-16].

Plasma processing techniques, such as Plasma-Enhanced Chemical Vapor Deposition (PECVD) [14-16] and Plasma-Enhanced Atomic Layer Deposition (PEALD) [17-19], have been invaluable in nanomaterial synthesis. This paper focuses on Atmospheric Pressure Plasma Jets (APPJs) [20-22], a disruptive technology that operates at ambient pressure, offering significant advantages over low-pressure methods [23-25]. This review emphasizes the novelty of APPJ processing, particularly its cost-effectiveness and scalability, which facilitate large-scale surface modification at ambient pressure, make it ideal for industrial applications [26-28]. This review also explores the impact of recent advancements in APPJ design [29-31], such as microfluidic configurations, resulting in significant enhancements in efficiency, power, and user-friendliness [32-34]. Despite its potential, plasma processing poses challenges [35-37], requiring expertise and precise control for parameter optimization [38-40]. Additionally, equipment and process optimization may incur high costs, potentially impeding widespread adoption [41-43]. Material compatibility with plasma treatment also demands careful consideration for specific applications [44-46].

Contribution of this Review: This paper stands out by:

- Focusing on APPJ processing: We explore APPJ applications across industries, aiming to create tailored nanomaterials [47-49].
- Addressing scalability and environmental considerations: Confronting challenges in plasma processing, especially scalability [50-52], and environmental sustainability, advocating responsible development [53-55].
- Promoting collaborative research: Through fostering collaboration and overcoming hurdles, we seek to unleash APPJ-processed nanomaterials' full potential and drive industry advancements [56-58].

This review offers a comprehensive and critical examination of atmospheric-pressure plasma jet (APPJ) processing for nanomaterial fabrication. It connects theoretical insights with practical applications through thorough analyses backed by evidence. We delve into the wide-ranging applications, tackle existing

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challenges, and outline future prospects of APPJ-processed nanomaterials across various industries. Our exploration aims to facilitate informed decision-making and foster transformative innovation in this rapidly evolving field.

2. PLASMA PROCESSING TECHNIQUES

Plasma processing techniques for synthesizing and modifying nanomaterials fall into two main categories: low-pressure and atmospheric-pressure plasmas [59-61].

2.1. Low-Pressure Plasma Techniques:

Plasma-Enhanced Chemical Vapor Deposition (PECVD): PECVD is a method that deposits thin films onto substrates by subjecting a precursor gas to a plasma discharge [79]. It facilitates the deposition of diverse nanomaterials such as metals, semiconductors, dielectrics, and polymers, enhancing scalability for commercial applications. The process involves precursor gas introduction, plasma discharge, and thin film deposition, with advanced PECVD systems incorporating novel gas delivery mechanisms, advanced plasma generation techniques, and robotic substrate handling systems [78].

Plasma-Enhanced Atomic Layer Deposition (PEALD): PEALD achieves atomic layer precision through alternating pulses of precursor and reactant gases. Recent advancements focus on enhancing thin film deposition precision and uniformity, with innovative gas pulsing mechanisms, advanced plasma sources, and new control systems [77].

Figure **1** illustrates a schematic of a modern PECVD reactor, delineating key components and their arrangement [65-67].

1. Vacuum Chamber: Forms the core of the PECVD system, maintaining a controlled environment for thin film deposition. Typically composed of stainless steel or quartz, it sustains low pressure (around 100 mTorr).

2. Precursor Gas Inlet: Dedicated gas inlets introduce precursor gases like silane (SiH4) or silicon dioxide (SiO2) into the chamber. Mass flow controllers regulate these gases, ensuring precise deposition rates and film properties.

3. Plasma Generation Region: Utilizes methods such as radio frequency (RF) or microwave (MW) sources to generate plasma within the reactor. RF and MW energy induces gas molecule collisions and dissociation, producing ions, electrons, and neutral radicals.

4. Substrate Holder: Supports the substrate, where thin film deposition occurs. Typically heated to control film growth and enhance quality.

Process of Precursor Gas Introduction, Plasma Discharge, and Thin Film Deposition [68-70]:

1. Precursor Gas Introduction: Controlled gas inlets introduce precursor gases into the vacuum chamber, selected based on the desired thin film material.

2. Plasma Discharge: RF or MW energy generates plasma within the chamber, providing the energy needed to dissociate precursor gases into reactive species.

3. Thin Film Deposition: Reactive species from the plasma interact with the substrate surface, forming a thin film. Film growth is regulated by parameters like precursor gas flow rates, plasma power, and substrate temperature.

Key Components of a Contemporary PECVD Reactor [71-73]:

1. Vacuum Pump: Evacuates the chamber and sustains low pressure.

2. Gas Flow Control System: Regulates precursor and plasma gas flow into the chamber.

3. Plasma Power Supply: Provides energy for plasma generation.

4. Substrate Temperature Controller: Maintains substrate temperature for deposition.

5. Monitoring and Control Systems: Track and regulate critical parameters like pressure, gas flow rates, plasma power, and substrate temperature.

Cutting-edge PECVD systems incorporate advanced features to enhance film quality, deposition rates, and process uniformity. These advancements include [74-76]:

- Novel Gas Delivery Mechanisms: Innovative methods like remote plasma sources and plasma

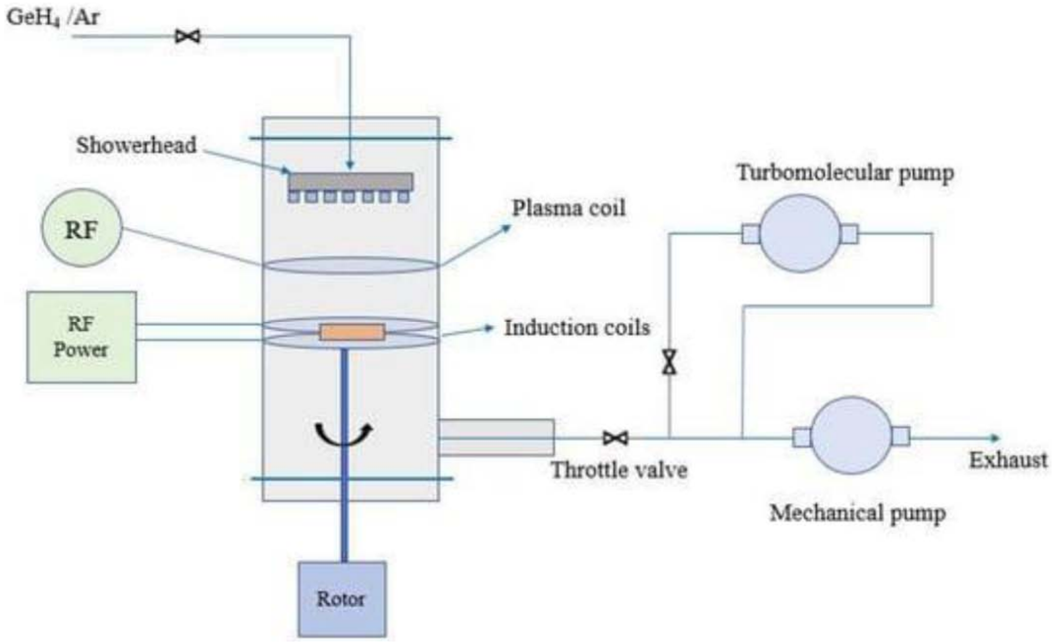

Figure 1: Schematic of a PECVD reactor used for deposition of the Ge thin films [67-69].

jet techniques enhance uniformity and control over film properties.

- Advanced Plasma Generation Techniques: Sophisticated methods such as inductively coupled plasma and electron cyclotron resonance sources allow precise plasma control, optimizing film characteristics.

- Robotic Substrate Handling Systems: Automated systems improve process automation and minimize contamination risks in substrate handling.

- Intelligent Control Systems: Incorporating machine learning and artificial intelligence algorithms, intelligent control systems optimize process parameters, ensuring consistent, high-quality thin films.

PEALD, or Plasma-Enhanced Atomic Layer Deposition, is a thin film deposition method that employs alternating pulses of precursor and reactant gases to achieve atomic layer precision [77-79]. It initiates with the introduction of a precursor gas, which adheres to the substrate surface. Then, a reactant gas is introduced, prompting a chemical reaction with the precursor and the substrate, leading to the deposition of a single monolayer of material. This cycle repeats until the desired film thickness is attained [80-82]. Key components and their arrangement are illustrated in Figure **2**.

- The gas delivery system introduces precursor and reactant gases into the reactor chamber. Utilizing mass flow controllers, it ensures precise control over gas flow rates.

- The plasma source generates a partially ionized gas, known as plasma, which excites precursor gas molecules, enhancing their reactivity. Various types of plasma sources can be employed in a PEALD reactor, including RF (radio frequency) plasma, microwave plasma, and inductively coupled plasma.

- The substrate is the material where the thin film is deposited. It is commonly positioned on a heated stage to facilitate the deposition process.

- The pumping system evacuates the reactor chamber to create a vacuum, crucial for controlled delivery of gases to the substrate.

Advancements in PEALD [83-85]:

Recent PEALD advancements prioritize enhancing thin film deposition precision and uniformity. This progress stems from the development of novel gas pulsing mechanisms, plasma sources, and control systems.

Gas Pulsing Mechanisms [86]:

Innovative gas pulsing mechanisms have emerged to refine deposition control, enabling precise timing of

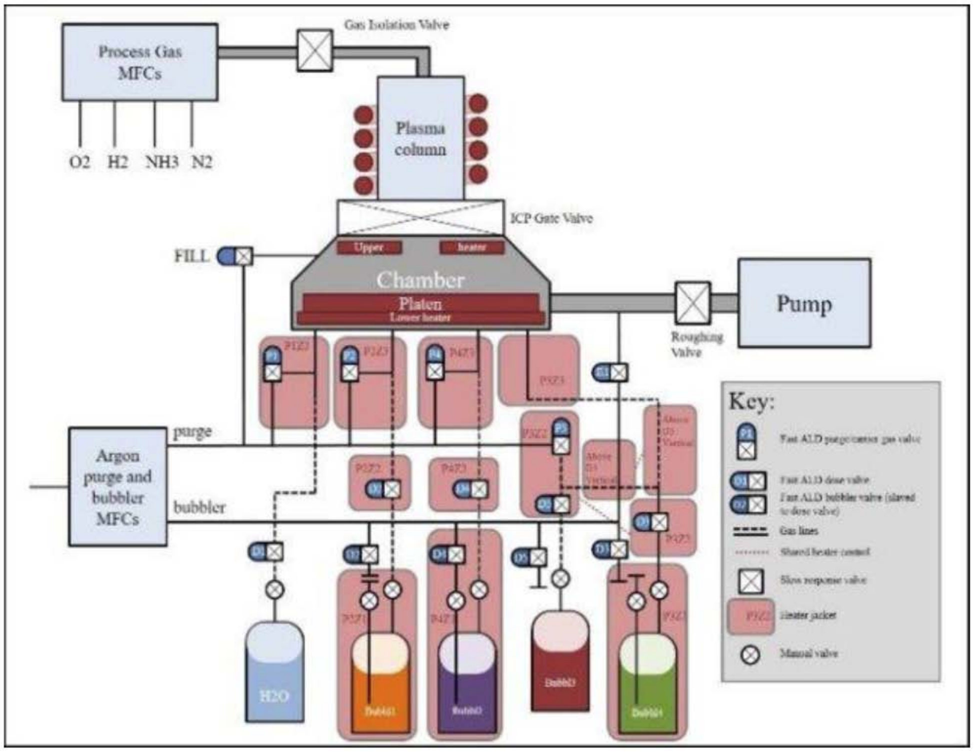

Figure 2: Schematic of a PEALD reactor [49-51].

gas pulses for enhanced film quality. One approach employs a valve series to regulate gas flow into the reactor chamber, while another utilizes a piezoelectric actuator to vibrate the substrate, promoting more uniform gas molecule adsorption onto the substrate.

Plasma Sources [58-60]:

Advanced plasma sources have emerged to produce uniform plasmas, crucial for achieving consistent film deposition. For instance, microwave discharge and RF discharge are two types of plasma sources designed to enhance uniformity in plasma generation.

Control Systems [55-57]:

New control systems enhance deposition precision by enabling finer control over gas flow rates, plasma power, and substrate temperature. One type utilizes PID controllers for gas flow rates, while another employs fuzzy logic controllers for plasma power regulation.

Applications of PEALD [51-53]:

PEALD, a versatile thin film deposition method, deposits various materials like semiconductors, dielectrics, and metals, making it valuable for nanodevice fabrication. Advancements in PEALD enhance precision and uniformity through innovative gas pulsing, plasma sources, and control systems, promising applications in nanodevice fabrication and advanced materials [52-54].

Table **1** provides a brief comparison of two low-pressure plasma techniques: PECVD and PEALD. PECVD deposits thin films using high-pressure plasma, commonly for electronic devices. PEALD utilizes alternating precursor and reactant gas pulses for atomic layer precision deposition. Applications include electronics, optoelectronics, and coatings for PECVD, while PEALD is suitable for semiconductor devices and nanodevices.

Table **2** delineates the key components of a modern PECVD reactor, clarifying their roles in the thin film deposition process [43-45]. Its significance lies in facilitating comprehension of the intricate workings of a contemporary PECVD reactor and its pivotal role in thin film deposition [81-83]:

Table **2** elucidates the intricate process of PECVD by outlining key components and their functions, making thin film deposition more tangible. It underscores critical interactions among components and facilitates effective troubleshooting. Moreover, it guides reactor design and optimization, fostering interdisciplinary understanding and collaboration

Table 1: Comparison of Low-Pressure Plasma Techniques [46-48]

Technique	Description	Applications
Plasma-Enhanced Chemical Vapor Deposition (PECVD)	Deposition of thin films onto substrates using a precursor gas subjected to a plasma discharge. Enables deposition of various nanomaterials like metals, semiconductors, dielectrics, and polymers.	Electronics, optoelectronics, coatings
Plasma-Enhanced Atomic Layer Deposition (PEALD)	Thin film deposition technique utilizing alternating pulses of precursor and reactant gases for atomic layer precision. Adsorption and chemical reaction cycles to achieve desired film thickness.	Semiconductor devices, nanodevice

Table 2: Key Components of a Contemporary PECVD Reactor [43-45]

Component	Description
Vacuum Pump	Evacuates the chamber and maintains low pressure.
Gas Flow Control System	Regulates the flow of precursor gases and plasma gases.
Plasma Power Supply	Provides energy for plasma generation.
Substrate Temperature Controller	Maintains desired substrate temperature during thin film deposition.
Monitoring and Control Systems	Track and regulate critical parameters like pressure, gas flow rates, plasma power, and substrate temperature.

among physicists, chemists, engineers, and material scientists. In essence, Table **2** serves as a gateway to comprehending PECVD reactor functionality and its pivotal role in thin film deposition.

2.2. Atmospheric-Pressure Plasma Techniques

Atmospheric Pressure Plasma Jets (APPJs): APPJs enable the synthesis and modification of nanomaterials through nucleation, growth, etching, deposition, and surface modification [80]. Recent advancements include more efficient plasma generation, improved nozzle design, and enhanced substrate interaction, making APPJs a versatile tool for various applications, such as antimicrobial coatings, drug delivery systems, and solar cells [40-42].

Plasma processing techniques offer versatility in nanomaterial synthesis and modification, allowing precise control over size, shape, and composition, and scalability for large-scale production [10-13]. Challenges include precise control over plasma parameters and costliness [14-15]. Nonetheless, plasma processing techniques remain promising for various applications, with ongoing technological advancements. Figure **3** illustrates an APPJ device schematic, showcasing advancements in atmospheric-pressure plasma technology, including more efficient plasma generation, nozzle design, and substrate interaction, with key components and advancements explained [78-80].

1. High-Voltage Discharge:

- Utilizes RF power for non-thermal plasma generation, minimizing substrate heat damage.
- Incorporates dielectric barrier for enhanced plasma stability and control.

2. Gas Flow and Nozzle Design:

- Utilizes precise gas flow system for optimized plasma characteristics and uniform delivery.
- Adopts converging-diverging nozzle design for accelerated plasma jet, achieving higher velocities and penetration depths.
- Features multi-nozzle configuration to expand treatment area and enhance throughput.

3. Plasma Jet Generation and Substrate Interaction:

- Generates focused plasma jet with adjustable diameter and shape for precise substrate targeting.
- Employs customized gas mixtures to achieve desired plasma properties.
- Utilizes grounded substrate stage to facilitate ion bombardment and enhance plasma-substrate interaction.

Applications in Nanomaterial Synthesis and Modification [37-39]:

- Nanomaterial Nucleation: APPJs promote nanomaterial nucleation by providing a dense concentration of reactive species initiating growth processes.
- Nanomaterial Growth: Control over size, morphology, and crystal structure is achieved by tailoring plasma parameters and gas mixtures.
- Nanomaterial Etching: Selective etching of materials or removal of surface contaminants from nanostructures with precision and minimal damage.
- Nanomaterial Deposition: Thin film deposition and coatings onto various substrates enhance properties and functionalities.
- Surface Modification: Altering surface properties like wettability, adhesion, and biocompatibility for diverse applications.

Overall, APPJs serve as versatile and potent tools for synthesizing and modifying nanomaterials, enabling the development of tailored advanced materials for diverse applications. Tables **3** and **4** succinctly summarize the key features, advantages, and challenges of APPJs. Table **3** provides a concise overview of essential APPJ characteristics, emphasizing their versatility and application potential across three main categories [75-77]:

1. High-Voltage Discharge:

- Description: Utilizes high-frequency RF power to generate non-thermal plasma, minimizing substrate heat damage.
- Key features: High-frequency power source, dielectric barrier for plasma stability.

2. Gas Flow and Nozzle Design:

- Description: Emphasizes controlled gas flow's importance in optimizing plasma characteristics and ensuring uniform delivery, along with the impact of nozzle design on plasma jet velocity and penetration depth.
- Key features: Controlled gas flow system, converging-diverging nozzle design for enhanced velocities and depths, multi-nozzle configuration for increased treatment area and throughput.

3. Plasma Jet Generation and Substrate Interaction:

- Description: Focuses on generating focused plasma jets with controllable diameter and shape, tailored gas mixtures for specific plasma properties, and utilizing a grounded substrate stage for enhanced plasma-substrate interaction.
- Key features: Focused plasma jet with controllable diameter and shape, tailored gas mixtures, grounded substrate stage.

Table 3: Characteristics of APPJs [34-36]

Component/Advancement	Description
1. High-Voltage Discharge	Utilizes high-frequency (RF) power source for non-thermal plasma generation, minimizing substrate heat damage.
	Incorporates a dielectric barrier for plasma confinement, enhancing stability and control.
2. Gas Flow and Nozzle Design	Employs a controlled gas flow system for optimized plasma characteristics and uniform delivery.
	Converging-diverging nozzle design accelerates plasma jet, achieving higher velocities and penetration depths.
	Multi-nozzle configuration expands treatment area and enhances throughput.
3. Plasma Jet Generation and Substrate Interaction	Generates focused plasma jet with controllable diameter and shape.
	Uses tailored gas mixtures for desired plasma properties.
	Grounded substrate stage facilitates ion bombardment and enhances plasma-substrate interaction.

Table 4: Applications of APPJs in Nanomaterial Synthesis and Modification [31-33]

Application	Description
Nanomaterial Nucleation	Promotes nucleation by providing a high density of reactive species that initiate and catalyze growth.
Nanomaterial Growth	Controls size, morphology, and crystal structure by tailoring plasma parameters and gas mixtures.
Nanomaterial Etching	Selectively etches materials or removes surface contaminants from nanostructures with precision.
Nanomaterial Deposition	Deposits thin films and coatings onto various substrates, enhancing properties and functionalities.
Surface Modification	Modifies surface properties like wettability, adhesion, and biocompatibility for diverse applications.

Table **4** outlines five main applications of APPJs in nanomaterial synthesis and modification, along with brief descriptions [72-74]:

1. Nanomaterial Nucleation:

- Description: APPJs promote the formation of nanoparticles by providing a high density of reactive species that catalyze growth through energetic collisions with surrounding atoms or molecules.

2. Nanomaterial Growth:

- Description: Plasma parameters and gas mixtures in APPJs control the size, shape, and crystal structure of nanoparticles, enabling tailored growth by adjusting plasma power or frequency and using different gas mixtures.

3. Nanomaterial Etching:

- Description: APPJs selectively etch material from nanoparticles or remove surface contaminants by generating reactive species that break down the material being etched, shaping nanoparticles or preparing surfaces for further processing.

4. Nanomaterial Deposition:

- Description: APPJs deposit thin films and coatings onto substrates by creating a vapor of material that condenses onto the substrate, enhancing properties of existing nanoparticles or creating new ones with specific properties.

5. Surface Modification:

- Description: APPJs modify surface properties like wettability, adhesion, and biocompatibility by breaking surface bonds and allowing attachment of new functional groups, improving material performance for various applications.

In summary, APPJs offer versatile applications in nanomaterial synthesis and modification, allowing control over nanoparticle properties and surface characteristics through tailored plasma parameters and gas mixtures.

Figure **3** showcases advancements in atmospheric-pressure plasma technology through a schematic of the APPJ device. Key components include nitrogen gas, AC high voltage power supply, resistor, porous alumina, quartz tube, inner electrode, outer electrode, and nozzle. Advancements focus on more efficient plasma generation, improved nozzle design, and enhanced substrate interaction. These advancements

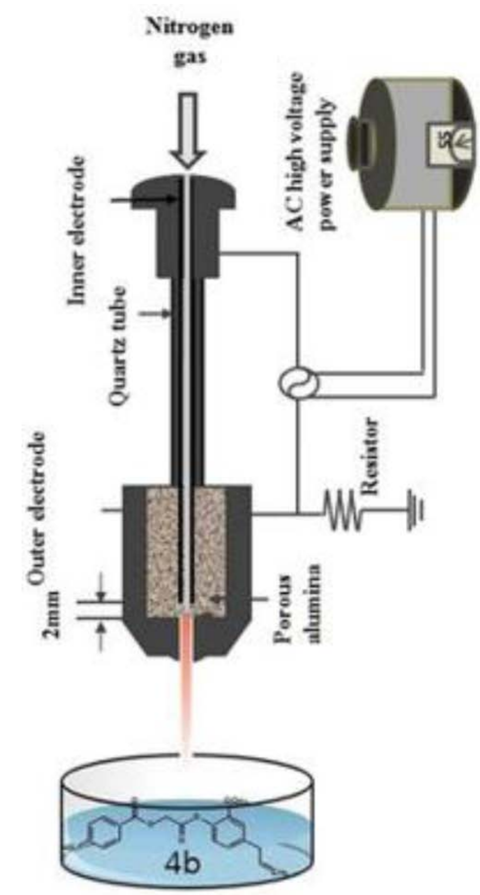

Figure 3: Schematic of an APPJ device [29-31].

lead to lower power consumption, increased plasma penetration depth, and more uniform substrate treatment, contributing to a more efficient and user-friendly APPJ device for diverse applications.

Nanofluids

Nanofluids, suspensions of nanoparticles in base fluids like water or oil, offer enhanced properties such as increased thermal and electrical conductivity, as well as greater surface area (225-227). Their fabrication typically involves two steps: nanoparticle synthesis using methods like chemical precipitation or physical vapor deposition, followed by dispersion within the base fluid using techniques like ultrasonication or stirring [22-24]. Surface modifications are often conducted to enhance stability and prevent aggregation. Nanofluids find applications in various sectors including heat transfer, lubrication, biomedical cooling, and solar thermal systems [19-21]. Plasma-assisted nanofluid synthesis has gained traction due to advantages like better particle size control, higher purity, and scalability [16-18]. Current research focuses on developing methods to enhance nanofluid properties, such as improving thermal conductivity, lubrication, and antimicrobial activity through techniques like nanoparticle coating with materials like copper, silver, molybdenum disulfide, or graphite [3, 4]. Figure **4** illustrates the two-step process of nanofluid synthesis involving nanoparticle synthesis and dispersion. Nanoparticle Synthesis:

1. Synthesize nanoparticles using methods like chemical precipitation, physical vapor deposition, or laser ablation, tailored to desired properties such as size, shape, and composition.

Nanoparticle Dispersion:

2. Disperse nanoparticles into a base fluid to form the nanofluid. Overcoming agglomeration challenges:

- Ultrasonication: Employ high-frequency sound waves to disperse nanoparticles evenly.

- Mechanical stirring: Utilize shear forces from a stirrer to break up agglomerates.

- Chemical dispersants: Apply molecules adsorbing onto nanoparticle surfaces to prevent agglomeration.

Additional Notes:

- "Groper-sante" mentioned in the figure likely denotes a specific dispersant or additive enhancing nanofluid stability.

- Optimal synthesis and dispersion methods vary depending on specific nanoparticles and base fluid characteristics.

Table **5** compares traditional and plasma-assisted nanofluid synthesis methods across various aspects [17]. Here is a summary of the key points [63-65]:

Table **5** indicates plasma-assisted methods may provide advantages in particle size control, purity, and scalability for large-scale production. Further research is needed to confirm these benefits and address associated limitations or challenges.

Carbon Nanotubes

Carbon nanotubes (CNTs) are cylindrical nanostructures composed of carbon atoms arranged in a hexagonal lattice, possessing exceptional strength and stiffness, superior thermal and electrical conductivity, and a high aspect ratio [5]. Figure **5** illustrates the structures of single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), and multi-walled carbon nanotubes (MWCNTs) [8-10]. SWCNTs consist of a

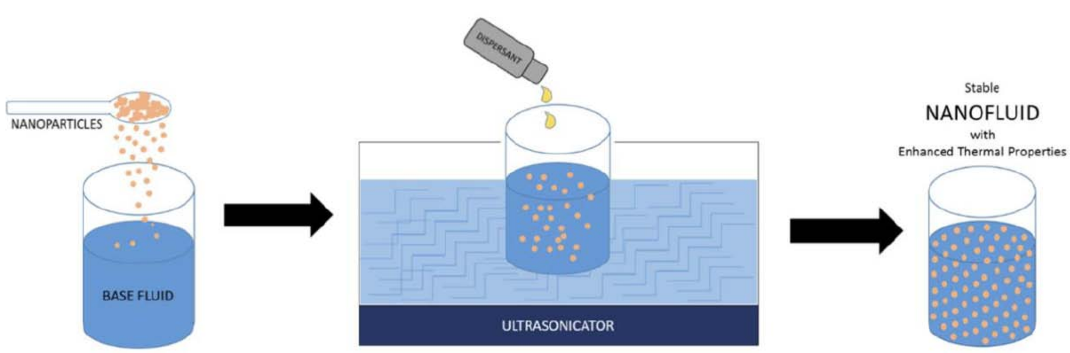

Figure 4: Nanofluids synthesis: The two-step process of nanofluids synthesis: (1) nanoparticle synthesis and (2) nanoparticle dispersion [14-16].

Table 5: Comparison of Traditional Nanofluid Synthesis vs. Plasma-Assisted Nanofluid Synthesis [11-13]

Aspect	Traditional Methods	Plasma-Assisted Methods	Evidence/Discussion
Control over Particle Size	Limited control, prone to agglomeration	Potential for improved control through tailored plasma parameters; requires rigorous studies with quantitative data to confirm and optimize	The table mentions potential for better size control with plasma methods but emphasizes the need for more research with evidence like size distribution graphs and data analysis to confirm and address limitations.
Purity of Nanoparticles	Moderate purity; potential for impurities from solvents or precursors	Potential for higher purity due to in-situ cleaning by plasma; needs comprehensive analysis to quantify purity improvement	Like size control, plasma methods have the potential for higher purity, but the table highlights the need for comprehensive analysis (e.g., elemental analysis, spectroscopy) to quantify the actual improvement and identify potential contamination sources in plasma synthesis.
Scalability for Large-Scale Production	Often challenging due to limitations in reactor size and batch processing	Potential for scalability with continuous flow reactors; further research needed to address feasibility and economic viability for large-scale production	The table acknowledges the inherent challenges of scaling traditional methods and mentions the potential of continuous flow reactors for plasma methods. However, it emphasizes the need for further research to assess the feasibility and economic viability of large-scale plasma-assisted synthesis.
Scalability for Large-Scale Production	Challenging	Not mentioned in the table	The table only mentions the scalability challenges of traditional methods and does not explicitly discuss it for plasma-assisted methods. This suggests that scalability might be an issue for both methods, but more information is needed on plasma-assisted scalability.

single layer of carbon atoms rolled into a cylinder, whereas MWCNTs comprise multiple layers of carbon atoms rolled into concentric cylinders [6]. With properties like high tensile strength, stiffness, and thermal/electrical conductivity surpassing copper and metals, CNTs find applications in composite materials, electronics, energy storage, and water filtration [7-8]. As technology advances, CNTs are expected to play a pivotal role in various sectors [9]. Plasma processing, a versatile technique, facilitates CNT synthesis, functionalization, and alignment. PECVD, a common method, synthesizes CNTs by subjecting a hydrocarbon gas like methane to a plasma discharge in a vacuum chamber, where reactive species deposit on a substrate to form CNTs [10]. Plasma processing can also functionalize CNTs by attaching chemical groups to modify their properties, such as enhancing wettability and dispersion in aqueous solutions [10]. Additionally, plasma processing aids in aligning CNTs, enhancing their electrical conductivity and mechanical strength [11]. Overall, plasma processing offers a powerful tool for CNT production, holding promise for diverse applications [60-62].

Table **6** presents applications and properties of carbon nanotubes (CNTs), highlighting their potential across various fields [57-59]:

Applications:

- Composite materials: Enhance strength, stiffness, and conductivity in aerospace, automotive, and sporting goods.
- Electronics: Ideal for transistors, logic devices, sensors, conductive films, and electrodes.
- Energy storage: Create high-performance electrodes for batteries and supercapacitors, enabling faster charging and longer storage.
- Water filtration: Used in membranes to remove pollutants and bacteria, offering sustainable water production and desalination.

Properties:

- High tensile strength and stiffness: Ideal for reinforcement in composites.

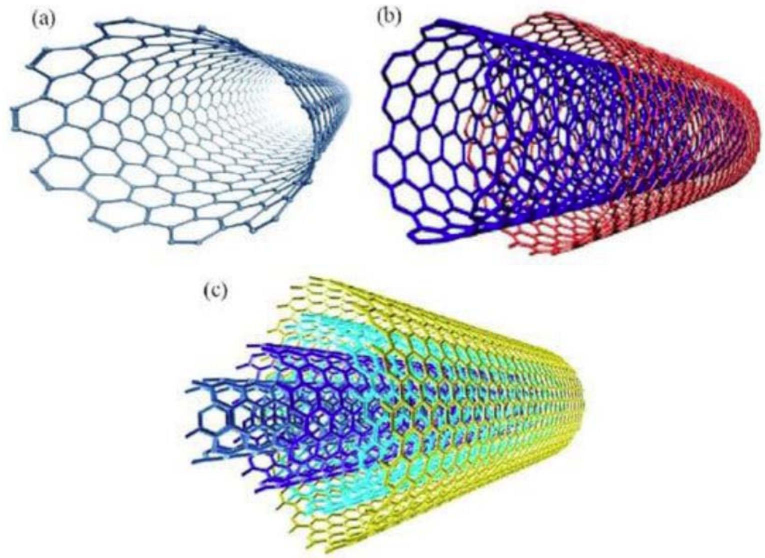

Figure 5: Structure of (**a**) SWCNT, (**b**) DWCNT, and (**c**) MWCNT [7-9].

- Excellent electrical and thermal conductivity: Superior to copper and diamond in some cases, valuable for electronics and heat dissipation.
- High energy density and durability: Suitable for energy storage applications.
- Removal of pollutants from water: Effective adsorption and removal of contaminants due to high surface area.

Overall, CNTs showcase vast potential across industries, revolutionizing areas like energy, electronics, and environmental sustainability.

3. ADVANCED COATINGS

Advanced coatings play a crucial role in aerospace and electronics, enhancing component performance, durability, and reliability. In aerospace, thermal plasma spray coating is a significant technology for applying thermal barrier coatings on turbine blades. In electronics, plasma processing techniques are used for conformal and conductive coatings on circuits [82]. Plasma-processed advanced coatings offer improved durability, functionality, and biocompatibility, making them suitable for diverse applications [81].

In electronics, they improve electrical conductivity and protect against moisture and dust. Plasma processing, including techniques like PECVD and PEALD, enables the deposition of various materials with complex structures. For instance, in aerospace, plasma processing is used for thermal barrier coatings on turbine blades. In electronics, it's used for conformal and conductive coatings on circuits. These coatings offer improved durability, functionality, and biocompatibility, making them suitable for diverse applications. Overall, plasma-processed advanced coatings hold significant potential for enhancing product performance across industries.

4. GRAPHENE

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, exhibits remarkable properties such as high strength, conductivity, and flexibility [83]. Plasma processing techniques, including PECVD, are utilized for synthesizing and modifying graphene, enabling the production of high-quality graphene with

Table 6: Applications and Properties of Carbon Nanotubes [4-6]

Application	Key Properties of CNTs
Composite Materials	High Tensile Strength and Stiffness
Electronics	Excellent Thermal and Electrical Conductivity
Energy Storage	High Energy Density and Durability
Water Filtration	Removal of Pollutants from Water

Table 7: Applications of Plasma-Processed Advanced Coatings [1-3]

Industry	Application
Aerospace	Thermal barrier coatings, anti-corrosion coatings, radar-absorbent coatings
Electronics	Conformal coatings
Automotive	Wear-resistant coatings, scratch-resistant coatings, self-cleaning coatings
Medical	Biocompatible coatings, antimicrobial coatings, drug-delivery coatings
Energy	Solar cell coatings, fuel cell coatings, corrosion-resistant coatings for power plants
Textiles	Water-repellent coatings, flame-retardant coatings, antimicrobial coatings
Construction	Anti-graffiti coatings, self-cleaning coatings, weather-resistant coatings

tailored properties for various applications, including electronics, energy storage, water purification, composites, and biomedical applications [1].

Plasma processing, a versatile technique, is utilized for synthesizing and modifying graphene. In PECVD, a carbon-containing gas undergoes plasma discharge in a vacuum chamber, depositing graphene layers on the substrate. Plasma processing can also modify graphene by introducing functional groups or doping it with other elements, tailoring its properties for specific applications [3]. This technique enables the production of high-quality graphene with tailored properties for various applications, including electronics, energy storage, water purification, composites, and biomedical applications [2, 4].

Table **8** compares properties and applications of graphene before and after plasma processing. It illustrates graphene's unchanged fundamental properties post-plasma processing, particularly with PECVD. While thickness, strength, weight, and

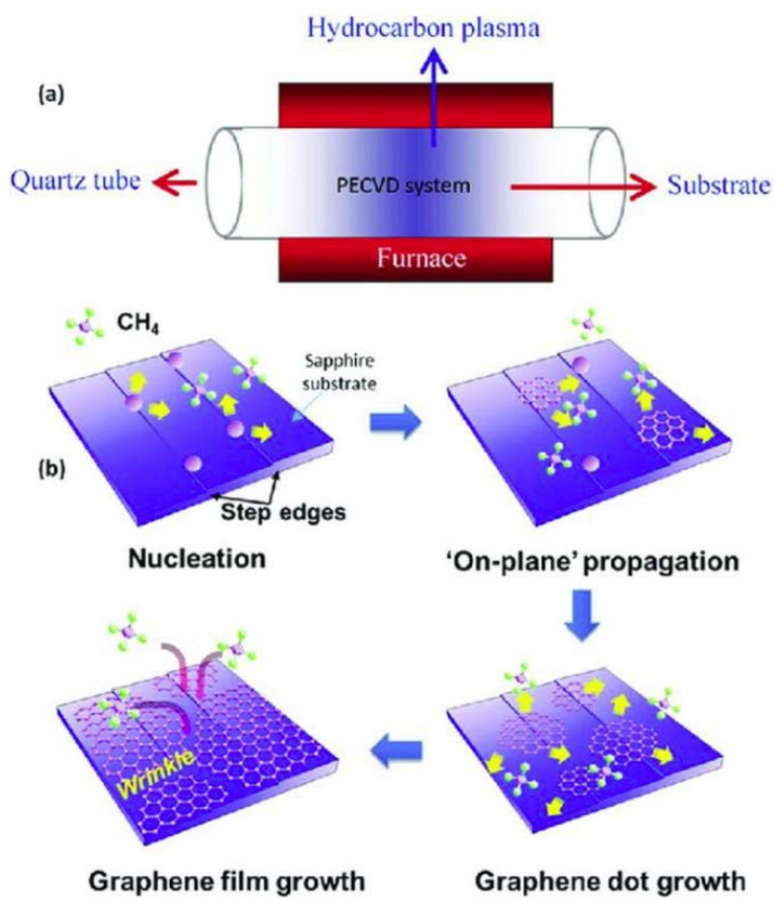

Figure 6: (**a**) PECVD system for nanographene film growth (**b**) Diagram of the catalyst-free direct-growth of graphene on sapphire via a CVD process [2-4].

Table 8: Properties and Applications of Graphene Before and After Plasma Processing [3-5]

Property	Graphene (Before Plasma Processing)	Graphene (After Plasma Processing)
Thickness	Single layer of carbon atoms in a hexagonal lattice	Unchanged
Strength	Thinnest and strongest material known	Unchanged
Conductivity	Most conductive material known	Unchanged
Weight	Incredibly lightweight	Unchanged
Flexibility	Highly flexible	Unchanged
Impermeability	Impermeable to liquids and gases	Unchanged
PECVD System Growth	PECVD system for nanographene film growth	Catalyst-free direct-growth of graphene on sapphire via CVD process
Potential Applications	- Electronics: High conductivity and transparency for transistors, sensors, displays	- Enhanced catalytic activity for use in fuel cells (e.g., nitrogen-doped graphene)
	- Energy Storage: Large surface area and high conductivity for supercapacitors, batteries	- Tailored properties for specific applications through functionalization
	- Water Purification: Impermeability for water filtration membranes	
	- Composites: Strength and conductivity improvement when added to polymers, metals	
	- Biomedical Applications: Unique properties for drug delivery, tissue engineering, biosensors	

flexibility remain unaffected, enhanced catalytic activity, such as nitrogen-doped graphene, is noted. This process broadens graphene's application scope, notably in catalysis, while maintaining its existing functionalities across electronics, energy storage, and other sectors.

5. CHARACTERIZATION TECHNIQUES

Characterizing nanomaterials is crucial for assessing their quality and properties to meet specific application requirements. Techniques include microscopy (TEM, SEM), spectroscopy (XRD, Raman spectroscopy), thermal analysis (TGA, DSC), surface analysis (XPS, AFM), and others (DLS, zeta potential measurement) [83]. These techniques provide essential information for understanding nanomaterial morphology, composition, thermal stability, surface chemistry, and particle size distribution [5-7].

Various techniques are employed for this purpose:

- Microscopy techniques (e.g., TEM, SEM) visualize size, shape, and morphology.
- Spectroscopy techniques (e.g., XRD, Raman spectroscopy) determine crystal structure and composition.
- Thermal analysis techniques (e.g., TGA, DSC) study thermal properties like melting point.
- Surface analysis techniques (e.g., XPS, AFM) examine surface chemistry and topography.
- Other techniques (e.g., DLS, zeta potential measurement) measure particle size distribution and surface charge [14].

Table **9** serves as a quick reference, summarizing key characterization techniques, their purposes, and importance in assessing nanomaterial quality and properties. Here is a breakdown of the information in Table **9** [48-50]:

Main Purpose

Table **9** serves as a concise guide for researchers and professionals dealing with nanomaterials, detailing important characterization techniques, their purposes, and significance in evaluating nanomaterial quality and properties.

Key Techniques:

1. TEM: High-resolution visualization of nanomaterial size, shape, and morphology.
2. SEM: Detailed examination of nanomaterial surface features and elemental composition.
3. XRD: Determination of nanomaterial crystal structure and composition.

4. Raman Spectroscopy: Analysis of nanomaterial molecular composition and crystal structure.

5. TGA: Study of nanomaterial thermal properties, aiding in assessing thermal stability.

6. DSC: Measurement of heat flow during phase transitions in nanomaterials.

7. XPS: Investigation of nanomaterial surface chemistry and elemental composition.

8. AFM: High-resolution imaging and topographical details of nanomaterial surfaces.

9. DLS: Measurement of nanoparticle size distribution in solution.

Importance of Each Technique:

- TEM and SEM: Crucial for understanding nanomaterial morphology and surface features.

- XRD and Raman Spectroscopy: Essential for determining nanomaterial crystal structure and composition.

- Thermal Analysis Techniques (TGA and DSC): Critical for assessing nanomaterial thermal stability.

- XPS and AFM: Important for studying nanomaterial surface chemistry and topography.

- DLS: Crucial for controlling nanoparticle behavior in colloidal systems.

Overall, Table **9** offers a valuable overview of essential nanomaterial characterization techniques, aiding researchers, and professionals in making informed decisions for specific applications.

6. APPLICATIONS

Plasma-processed nanomaterials have extensive applicability across industries such as energy, electronics, and healthcare. Examples include nanocrystalline silicon solar cells in solar panels, plasma-processed silicon nanowires in lithium-ion batteries, graphene in faster transistors and displays, and plasma-processed gold nanoparticles in cancer treatment [85]. These applications demonstrate the transformative impact and future potential of plasma-processed nanomaterials [84].

Table **10** outlines these applications, highlighting their transformative impact and future potential [39-41]. Overall, plasma-processed nanomaterials promise groundbreaking solutions across diverse sectors as plasma processing technology advances.

Table 9: Characterization Techniques for Nanomaterials [6-8]

Technique	Purpose	Importance
Transmission Electron Microscopy (TEM)	Visualizing size, shape, and morphology of nanomaterials	Provides high-resolution images, essential for understanding nanomaterial morphology.
Scanning Electron Microscopy (SEM)	Examining surface features of nanomaterials	Complements TEM, offering detailed surface information and aiding in morphological analysis.
X-ray Diffraction (XRD)	Determining crystal structure and composition	Enables identification of crystalline phases, crucial for assessing the material's properties.
Raman Spectroscopy	Analyzing molecular composition and crystal structure	Provides information on chemical bonding and molecular vibrations, aiding in material analysis.
Thermogravimetric Analysis (TGA)	Studying thermal properties, such as melting point	Assesses material stability and behavior under different temperature conditions.
Differential Scanning Calorimetry (DSC)	Measuring heat flow during phase transitions	Helps in understanding thermal behavior, aiding in applications with specific temperature needs.
X-ray Photoelectron Spectroscopy (XPS)	Studying surface chemistry of nanomaterials	Provides insights into the elemental composition and chemical states at the material's surface.
Atomic Force Microscopy (AFM)	Investigating surface topography and mechanical properties	Offers high-resolution imaging and precise topographical details of nanomaterial surfaces.
Dynamic Light Scattering (DLS)	Measuring particle size distribution	Essential for understanding size variations and ensuring uniformity in nanomaterial dimensions.
Zeta Potential Measurement	Assessing surface charge of nanomaterials	Critical for applications involving colloidal stability and interactions with other materials.

Table 10: Versatile Applications of Plasma-Processed Nanomaterials: A Cross-Industry Overview [9-11]

Industry	Application	Importance
Energy	Nanocrystalline silicon solar cells	Higher efficiencies compared to conventional cells
Energy	Battery technology	Increased energy and power density
Energy	Fuel cells	Introduction of catalysts with heightened activity
Electronics	Transistors	Amplified switching speeds and reduced power consumption
Electronics	Display materials	Superior brightness, contrast, and resolution
Healthcare	Drug delivery systems	More efficient and targeted drug delivery
Healthcare	Medical implants	Improved biocompatibility and durability
Healthcare	Diagnostic tools	Enhanced sensitivity and specificity
Real-world	Nanocrystalline silicon solar cells in solar panels	Commercial availability and widespread utilization
Real-world	Lithium-ion batteries with plasma-processed nanowires	Higher energy and power density compared to conventional counterparts
Real-world	Graphene and quantum dots in transistors, and displays	Faster transistors and displays with superior brightness and resolution
Real-world	Gold nanoparticles in drug delivery systems	More efficient and targeted treatment, especially in cancer

7. CHALLENGES AND FUTURE PROSPECTS

Despite its potential, plasma processing faces challenges such as contamination control, scalability, energy consumption, material compatibility, and equipment complexity. Addressing these challenges drives future research in plasma processing, focusing on plasma diagnostics, precise plasma tailoring, environmentally friendly processes, in-situ characterization, hybrid approaches, and application-specific optimization [86].

Plasma processing, while promising, faces several challenges [12-14]:

1. Contamination Control: Crucial for maintaining nanomaterial purity and properties.
2. Scalability: Large-scale production of specialized nanomaterials remains challenging.
3. Energy Consumption: High energy usage escalates costs and environmental impact.
4. Material Compatibility: Harsh conditions limit suitable nanomaterials.
5. Equipment Complexity: Costly equipment and specialized knowledge pose challenges.

Addressing these challenges drives future research in plasma processing [15-17]:

1. Plasma Diagnostics: Real-time data enhances process control.
2. Precise Plasma Tailoring: Allows for tailored nanomaterial properties.
3. Environmentally Friendly Processes: Reduces environmental impact.
4. In-situ Characterization: Facilitates real-time adjustments.
5. Hybrid Approaches: Enables complex nanomaterial structures.
6. Application-Specific Optimization: Enhances efficiency for specific applications.

CONCLUSION

This comprehensive review highlights the transformative potential of Atmospheric Pressure Plasma Jets (APPJs) in nanomaterial fabrication. Unlike traditional low-pressure techniques, APPJs provide significant advantages, such as cost-effectiveness and scalability. Recent advancements in APPJ design enable efficient and user-friendly modification of nanomaterials on a large scale. The unique ability of APPJs to operate at ambient pressure while achieving high precision in tailoring nanomaterial properties positions this technology as a disruptive tool in the field of nanotechnology.

The findings presented in this review underscore the importance of APPJ processing in bridging the gap between research and industrial applications. The technology's versatility is evident across various domains, including antimicrobial coatings, drug delivery systems, and solar cells, demonstrating its broad applicability. Moreover, the recent improvements in plasma generation, control mechanisms, and substrate interactions highlight the ongoing evolution of APPJ technology, suggesting a future where its applications could become even more widespread and impactful.

Looking forward, future research should focus on addressing the remaining challenges, such as enhancing scalability, reducing costs, and mitigating environmental impacts, to facilitate broader adoption. Collaborative efforts between academia and industry will be crucial in overcoming these barriers and unlocking the full potential of APPJs. Additionally, exploring new applications, such as in emerging fields like quantum materials and bioengineering, could open new avenues for innovation and application, further solidifying APPJs as a cornerstone technology in advanced material processing.

In conclusion, APPJ technology represents a significant advancement in nanomaterial processing, with the potential to revolutionize current practices and drive the development of next-generation materials. By fostering innovation and encouraging interdisciplinary collaboration, the continued exploration and refinement of APPJs will undoubtedly lead to groundbreaking advancements, making substantial contributions to both scientific research and industrial applications.

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This declaration is “not applicable” to this study.

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