



Fullerenes in Agriculture: Basics and Practical Applications

Suraj Prasad, Parshant Kaushik, VS Rana, Kailashpati Tripathi,
Rakesh Kumar and *Neethu Narayanan

Division of Agricultural Chemicals, ICAR-Indian Agricultural Research Institute,
New Delhi-110012, India

*Corresponding Author's email: neethu853@gmail.com

Nanoscience is the emerging trend in the materials and biology fields. Nanoscience simply deals with the study, understanding, and control of material at the nanoscale (e.g., atoms, molecules, macromolecules, quantum dots, and macromolecular assemblies) (Aqel et al., 2012; Dolmer, 2003). Recently, the development of nanoscale products has become increasingly dominant in agricultural as well as biological aspects of life. An advantage of microproducts over large-scale products is the size: a smaller size facilitates a quicker movement than larger systems because of the lower inertia of mass as well as less thermal distortion and vibration; this is a key to advanced technologies (Aqel et al., 2012; Mukherjee et al., 2016). More precisely, nanoscience includes many structures and techniques. One of the promising nanomaterial is fullerene—an all-carbon structure discovered in 1985 by Harold Kroto, Richard Smalley, and Robert Curl. Fullerene (named after architect Buckminster Fuller) are made entirely of carbon atoms arranged in a hollow, cage-like structure. A well-known fullerene, C_{60} , is composed of 60 carbon atoms that form a pattern of fused five-membered and six-membered rings. In this structure, each hexagon is alternately surrounded by hexagons and pentagons, while each pentagon is connected to five hexagons, giving C_{60} a soccer ball-like shape. Building on this unique structure, water-soluble derivatives of fullerenes (FWDs), such as $[C_{60}-OH]$ and $[C_{60}-COOH]$, have been widely used as nano theranostic agents (Saleem et al., 2018). Recently, researchers have expanded the potential applications of FWDs by exploring their interactions with plants in modern agriculture. Many studies indicate that FWDs, when used at the proper concentration, can be beneficial in agriculture and biotechnology. For example, treating bitter melon (*Momordica charantia*) seeds with 5–10 nmol/L of fullerenols $[C_{60}(OH)_{20}]$ increased biomass yield, fruit yield, and phytomedicine content by 54%, 128%, and 90%, respectively (Yemets et al., 2018). Similarly, in *Arabidopsis*, treatment with fullerenols $[C_{60}(OH)]$ increased the elongation of hypocotyls by 20–40% (Prylutska et al., 2019). They act as intracellular water binders, creating an extra water reserve that helps plants adapt to drought stress. (Kong et al., 2023) demonstrated that priming seeds with moderate concentrations of fullerenols significantly promoted seed germination under chemical stress induced by 15% polyethylene glycol (PEG). Fullerene derivatives, in certain concentrations, help to form plant produce enriched with selenium, zinc, and other useful microelements (Panova et al., 2023). Fullerene-based nanomaterials also serve as powerful antioxidants that detoxify reactive oxygen species (ROS) and activate antioxidant enzymes to protect plants from oxidative stress. For instance, $[C_{60}(OH)_{22} \cdot 8H_2O]_n$ increased antioxidant enzyme activities, reduced ROS accumulation in maize, and improved drought resistance (Buziashvili et al., 2020). C_{60} had significantly increased the uptake of Ammonium-N (from ~12.39 to ~50.92 $\mu\text{g/g/h}$) in wheat and iron (Fe) in maize and soybean (Wang et al., 2025).

Structure of Fullerene

Fullerenes, such as C₆₀, have a unique molecular structure that makes them fascinating-

- **Shape:** Fullerenes are composed of carbon atoms arranged in a spherical, ellipsoidal, or tubular shape. The most well-known fullerene, C₆₀, has a structure that resembles a soccer ball, consisting of 12 pentagonal and 20 hexagonal rings.
- **Bond Lengths:** In C₆₀, there are two types of bonds: the bonds between two hexagons (66 bonds) are shorter (1.38 Å), while the bonds between a hexagon and a pentagon (56 bonds) are longer (1.45 Å).
- **Hybridization:** The carbon atoms in fullerenes are sp² hybridized, but due to the curvature of the structure, the hybridization is slightly altered, resulting in a mix between sp² and sp³ hybridization.

Physical Properties of Fullerenes

Fullerenes, a unique allotrope of carbon, exhibit remarkable physical properties that have captivated the scientific community. These carbon-based nanostructures display exceptional pressure resistance, solubility characteristics, and temperature-dependent behavior, making them a subject of intense research and potential applications. (Rahman & Chung, 2013). One of the standout properties of fullerenes is their remarkable pressure resistance. When subjected to pressures exceeding 3000 atmospheres, fullerenes can recover their original shape, showcasing their durability (Rahman & Chung, 2013). In fact, a single C₆₀ molecule, when compressed to 75% of its original size, has an effective bulk modulus of 668 GPa, surpassing the strength of steel (160 GPa) and even diamond (442 GPa) (Troshin et al., 2005). Solubility is another distinguishing feature of fullerenes. Unlike other carbon allotropes, fullerenes are the only form of carbon that are soluble in organic solvents at normal temperatures. C₆₀ solutions exhibit unique optical and dielectric properties, including significant indices of refraction, a dielectric constant of around 4, large molecular volumes, and a Hildebrand solubility parameter comparable to 10 cal^{1/2} cm^{3/2}. The behavior and structure of fullerenes are also highly dependent on temperature. As the temperature increases, C₆₀ can be transformed into the larger C₇₀ fullerene (Radivoievyeh et al., 2023). Moreover, the structure of fullerenes can be altered under different pressure conditions (Radivoievyeh et al., 2023).

Chemical Properties of Fullerene

Fullerenes, the allotropes of carbon characterized by their unique spherical or ellipsoidal shape, exhibit a remarkable array of chemical properties that stem from their intricate molecular structure and electron configuration. One of the key features that gives rise to the chemical reactivity of fullerenes is their pyramidalized carbon atoms (Arco et al., 2011). The spherical form of fullerenes causes the carbon atoms to depart from planarity, leading to an increase in p-character of the sp² orbitals and a corresponding gain in reactivity (Troshin et al., 2005). The strong electron affinity of fullerenes is another critical property, arising from the occurrence of triply degenerate lowest empty molecular orbitals at relatively low energy levels. This makes them effective electron acceptors, allowing them to participate in a variety of redox reactions as oxidizing agents (Arco et al., 2011; Maroto et al., 2014). Fullerenes are generally stable but not entirely unreactive, and they can act as electrophiles in chemical reactions, showcasing their versatile reactivity (Troshin et al., 2005). When fullerenes are doped or crystallized with alkali or alkaline earth metals, they can exhibit superconductivity, a remarkable phenomenon that highlights the unique electronic properties of these carbon allotropes. Some fullerenes are inherently chiral, a property that has important implications in fields such as asymmetric catalysis and molecular recognition (Maroto et al., 2014). Additionally, the chemical reactivity of fullerenes is analogous to that of electron-deficient olefins, leading to the formation of cycloaddition products through additions at the 6,6-ring junctions.

Synthesis of fullerene

Physical Methods

Arc-Discharge and Resistive Heating- In this approach, graphite rods are vaporized by passing a high current through them in an inert helium atmosphere. This method—pioneered by Krätschmer and co-workers—operates at extreme conditions (approximately 1300 °C and pressures near 1 kbar). The carbon vapor that forms cools rapidly, condensing into a soot that contains fullerenes (primarily C₆₀ and C₇₀). Although this technique was a breakthrough in accessing usable quantities of fullerenes, it suffers from low yields (often less than 1%) and produces a complex mixture of carbon clusters that require extensive purification (e.g., via multiple cycles of high-performance liquid chromatography)(Krätschmer & Fostiropoulos, 1990; Krätschmer & Lamb, 1990).

Laser Vaporization- An alternative physical technique involves using a high-powered laser to ablate graphite. Early experiments by Kroto and co-workers employed laser vaporization to generate a hot carbon plasma, which subsequently cooled and self-assembled into fullerene molecules (Kroto et al., 1985). While the method confirmed the existence of C₆₀ and laid the groundwork for fullerene research, it shares many of the energy and yield limitations of the arc-discharge method.

Chemical Methods

Bottom-Up Assembly from Molecular Precursors- Chemical synthesis aims to construct fullerenes from smaller, well-defined organic molecules. One attractive strategy is to use curved polycyclic aromatic hydrocarbons as building blocks. For example, the synthesis of corannulene—first demonstrated by Barth and Lawton provides a fragment of the fullerene structure. Subsequent refinements by Scott and co-workers using flash vacuum pyrolysis (FVP) have enabled the conversion of tailored precursors into corannulene and further into fullerene fragments (Barth & Lawton, 1966). This bottom-up approach, however, remains challenging because it requires the introduction of curvature into otherwise planar aromatic systems.

Radical-Mediated Cyclization via Pyrolysis- Another chemical route involves designing halogenated (chlorinated or fluorinated) precursors that, upon high-temperature pyrolysis, undergo radical-mediated cyclizations. Scott and co-workers reported a method for synthesizing C₆₀ from a chlorinated precursor (C₆₀H₂₇Cl₃) using FVP, where radical formation and rearrangement of aryl groups “stitch” the molecular arms together into a closed cage (Scott et al., 2002). Later modifications—including the use of fluorine as a radical promoter to improve yield and control—have been proposed by (Kabdulov et al., 2010). In addition, Otero and co-workers demonstrated that depositing planar precursors onto a platinum surface can catalyze dehydrogenation and cyclization at lower temperatures, leading to nearly quantitative yields of fullerene derivatives (Otero et al., 2008).

General Application of Fullerene

Medicinal Applications

Fullerenes are extensively used in medicine for their antiviral properties, inhibiting HIV protease and hepatitis C replication through structural interference with viral enzymes (Mashino et al., 2005), and their antioxidant capacity neutralizes reactive oxygen species (ROS), offering neuroprotection and preventing oxidative damage in conditions like Alzheimer’s disease (Tokuyama et al., 1993). They enable targeted drug and gene delivery by functionalizing their hydrophobic core, enhancing cellular uptake of therapeutics like doxorubicin (Azzam & Domb, 2005), and serve as MRI contrast agents via gadolinium-encapsulated endohedral fullerenes (gado-fullerenes) (Shinohara, 2000). Antimicrobial applications leverage their ability to disrupt microbial membranes, combating pathogens such as *E. coli* and *Candida albicans* (Mashino et al., 1999). In dentistry, fullerenes aid in oral cancer diagnosis using nanoshells to target malignant cells (Shetty et al., 2013), bone regeneration via nanocrystalline hydroxyapatite in implants, and painless anesthesia through nanorobots that block nerve signals in dental pulp. They also treat dentin hypersensitivity by

occluding tubules and enhance orthodontic treatments with low-friction nanowires (Sen et al., 2022).

Electronic Applications

Fullerenes revolutionize electronics through organic photovoltaics (OPV), where C₆₀ acts as an electron acceptor to boost solar cell efficiency. Their integration into portable power devices, such as lithium-ion batteries and supercapacitors, improves energy storage density and charge cycles due to CNTs' high conductivity and surface area. CNTs are pivotal in flexible electronics for transistors and conductive films, enabling wearable tech, while their mechanical strength supports futuristic applications like ultra-durable cables and precision microscope tips (Yadav B.C. & Kumar R., 2008)(Fiorito et al., 2006).

Cosmetic Applications

In cosmetics, fullerenes function as anti-aging agents by scavenging free radicals (e.g., UV-induced ROS) to prevent collagen breakdown and wrinkles. They also act as stabilizers in formulations with zinc oxide, preventing oxidation and extending product shelf life in creams and serums (Vetrivel R, Navinselvakumar C, 2009).

Environmental Applications

Fullerenes address environmental challenges as photocatalysts in water purification, degrading pollutants like pesticides under light exposure. They neutralize biohazards (e.g., chemical toxins) through adsorption or decomposition. In automotive applications, they reduce emissions by enhancing catalytic converter efficiency and improving fuel economy as lubricant additives (Yadav B.C. & Kumar R., 2008).

Application of Fullerene in Agriculture

Enhanced Plant Growth and Yield

Fullerene C₆₀ and carbon nanotubes (CNTs) have been shown to significantly boost plant growth and yield. Their application improves water retention and increases biomass and fruit production in various crops. For instance, treating bitter melon seeds with fullerene not only enhances growth but also elevates the synthesis of key secondary metabolites such as cucurbitacin-B, lycopene, charantin, and insulin. In tomatoes, CNT exposure has been associated with up to a 200% increase in production. These findings underscore the potential of fullerene-based nanomaterials to revolutionize crop productivity by optimizing physiological processes in plants (Jha & Yadav, 2023).

Regulation of Pesticide Uptake

Fullerene-based nanomaterials are also being explored for their role in regulating pesticide uptake in crops. Studies have demonstrated that exposure to multiwalled carbon nanotubes (MWCNTs) or C₆₀ fullerenes can modulate the absorption of pesticides such as chlordane and DDT metabolites in plants like zucchini, corn, tomato, and soybean. In some cases, MWCNT coexposure reduced pesticide accumulation by 21–80%, while C₆₀ fullerenes exhibited species-specific effects—ranging from complete suppression of certain contaminants to moderate increases in accumulation. This application holds promise for reducing harmful pesticide residues in edible plant parts and enhancing food safety (Torre-Roche et al., 2012, 2013)

Antioxidant Properties of Fullerene Derivatives

The intrinsic antioxidant properties of water-soluble fullerene derivatives offer another valuable application in agriculture. These compounds are capable of intercepting major reactive oxygen species (ROS), thereby stabilizing mitochondrial membrane potential, reducing intracellular ROS production, and inhibiting lipid peroxidation. By mitigating oxidative stress, fullerene derivatives can protect plant cells from damage caused by environmental stressors, potentially enhancing overall plant vigor and resistance to stress-induced damage (Yin et al., 2009).

Eco-Friendly Nanocompositions for Nutrient and Stress Management

Advances in nanobiotechnology have led to the development of eco-friendly nanocompositions that combine fullerene C₆₀ with trace elements. These innovative formulations are designed to enrich soil nutrient content and improve the physiological state

of plants. Field and controlled studies have shown that such nanocompositions not only boost plant growth but also enhance stress resistance under conditions such as UV-B irradiation, drought, and nutrient deficiency. Their regulatory, adaptogenic, and immunomodulatory effects on plants present a promising strategy for sustainable agriculture (Panova et al., 2024).

Enhancement of Seed Germination

Fullerene-based compounds have been effectively used to improve seed germination and early plant development. Research involving the synthesis of water-soluble quaternary ammonium salts of iminofullerenes (IFQA) demonstrated that treatment of maize and *Arabidopsis* seeds resulted in significantly higher germination rates and a quicker onset of growth under both normal and drought conditions. This enhancement in germination efficiency is critical for establishing robust seedlings, ultimately leading to healthier and more productive crops (Liu et al., 2019).

Impact on Root Growth and Development

Not all effects of fullerene application are beneficial; certain studies have highlighted potential adverse impacts on plant morphology. For example, experiments with water-soluble fullerene C70 derivatives revealed a retardation of root growth, manifested as shortened root length and a loss of normal gravitropic response in transgenic seedlings. These findings emphasize the importance of precise formulation and dosage control when employing fullerene derivatives in agricultural settings to avoid negative impacts on root development (Liu et al., 2010).

Protection Against Heavy Metal (Copper) Toxicity

Fullerenes have also been investigated for their ability to mitigate heavy metal toxicity in plants. In studies involving *Cucumis sativus* (cucumber), exposure to excess copper resulted in symptoms such as impaired growth, leaf chlorosis, diminished photosynthetic activity, and increased lipid peroxidation. Application of water-soluble fullerene derivatives alleviated these toxic effects, suggesting that such nanomaterials could serve as protective agents against heavy metal stress by restoring physiological balance and enhancing plant health (Bityutskii et al., 2023).

Smart Delivery Systems and Nano-Agriculture

The unique carbon cage structure of fullerene-based nanomaterials makes them excellent candidates for smart delivery systems in agriculture. These materials can be engineered to transport agrochemicals—including fertilizers, pesticides, and even gene or drug molecules—directly to specific plant tissues or cells. This targeted delivery not only improves the efficiency of agrochemical use but also minimizes environmental impacts. As such, fullerene-based systems are at the forefront of the emerging field of nano-agriculture, which aims to sustainably enhance crop productivity through advanced nanotechnological solutions (Madankar et al., 2024).

Fullerenols as Free Radical Sponges in Plants

Fullerenols, which are polyhydroxy derivatives of fullerenes, act as potent free radical sponges in plant systems. They effectively scavenge a broad spectrum of reactive oxygen and nitrogen species, thereby reducing oxidative stress within plant cells. This free radical scavenging capability can enhance plant resilience against various abiotic stresses, contributing to improved crop health and productivity. The ability of fullerenols to neutralize damaging free radicals positions them as promising agents for stress management in agricultural applications (Shafiq et al., 2023).

Conclusion

Fullerenes—owing to their unique hollow, cage-like structure, ease of chemical modification, and exceptional physical and electronic properties hold many promise across diverse fields. While it is primarily focuses on applications in diagnostics, therapeutics, and dentistry, but its insights are equally relevant to agriculture. The ability of fullerenes to act as efficient radical scavengers, carriers for targeted nutrient delivery, and catalysts in chemical reactions suggests that these nanomaterials could be harnessed to address several agricultural challenges. For instance, their functional versatility could enable the development of smart

agrochemical delivery systems in plant that optimize nutrient use, reduce pesticide residues, and improve plant resilience against environmental stresses. Moreover, fullerenes might be integrated into soil remediation and water purification technologies, thereby enhancing crop productivity and sustainability. Overall, by bridging the gap between nanotechnology and agricultural science, fullerene-based innovations could pave the way for more sustainable and efficient farming practices, ultimately contributing to improved food security and environmental stewardship.

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