**Synthesis, Properties and Applications of Dendrimers in Chemistry, Materials Science and Nanotechnology**

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**ABSTRACT**

Dendrimers are radially symmetric, nanoscale molecules with well-defined, homogenous, and monodisperse structures. They have an outer shell, an inner shell, and a core that is normally symmetric. The concept of dendrimers, highlighting their unique structure and the controlled strategies used in their synthesis. It discusses the divergent and convergent methods of synthesis, explaining their advantages and challenges. The various types of dendrimers, such as Polyamidoamine (PAMAM), Polypropylenimine (PPI), and L-lysine-based dendrimers, showcasing their distinct characteristics and applications ranging from drug delivery, gene therapy, and imaging to sensing, catalysis, and optoelectronics, underscoring the versatility of dendrimers. Dendrimers are a wonderful option in the medical area due to their wide range of qualities, and this article discusses all of their various applications.

**Keywords-** Dendrimer; PPI; Nanoscale; PAMAM.

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IIIii**I. INTRODUCTION**

 Dendrimers words come from Greek words [Dendrons], which mean ‘tree’ [1]. Dendrimers are nano-sized, radially symmetric molecules with a well-defined, homogeneous, and monodisperse structure consisting of tree-like arms or branches (Figure 1). These hyperbranched molecules were first discovered by Fritz Vogtle in 1978 [2]. In the early 1980s, and, at the same time, independently by George R. Newcome. The second group called synthesised macromolecules, ‘arborols’ means, in Latin, ‘trees’ [3]. Dendrimers might also be called ‘cascade molecules, but this term is not as established as dendrimers. Dendrimers are nearly monodispersed macromolecules that contain symmetric branching units built around a small molecule or a linear polymer core. ‘Dendrimer’ is only an architectural motif and not a compound. Polyionic dendrimers do not have a persistent shape and may undergo changes in size, shape, and flexibility as a function of increasing generations. Dendrimers are hyperbranched macromolecules with a carefully tailored architecture, the end-groups (i.e., the groups reaching the outer periphery), which can be functionalized, thus modifying their physicochemical or biological properties. Dendrimers have gained a broad range of applications in supramolecular chemistry, particularly in host-guest reactions and self-assembly processes. Dendrimers are characterized by special features that make them promising candidates for a lot of applications. Dendrimers are highly defined artificial macromolecules, which are characterized by a combination of a high number of functional groups and a compact molecular structure. The emerging role of dendritic macromolecules for anticancer therapies and diagnostic imaging is remarkable [4]. The advantages of these well-defined materials make them the newest class of macromolecular nano-scale delivery devices. Dendritic macromolecules tend to linearly increase in diameter and adopt a more globular shape with increasing dendrimer generation [5].



**Figure 1: Common structure of dendrimer.**

 Therefore, dendrimers have become an ideal delivery vehicle candidate for explicit study of the effects of polymer size, charge, and composition on biologically relevant properties such as lipid bilayer interactions, cytotoxicity, internalization, blood plasma retention time, and according to the nature of end groups the dendrimers have very in shapes, stability, solubility, rigidity or flexibility and viscosity the number of generations [6]. Modification of the branching units’ changes density of the dendrimer’s molecule. This is very important for the host-guest chemistry, which makes use of areas of lower density to accommodate appropriate choice of the branching modules without any need for preformed vacant cavities.

**II. BIO COMPATIBILITY STUDIES OF DENDRIMERS**

 Dendrimers have some specific properties that capable them in biological usage and drug delivery vehicles in vivo or drug design. For this purpose, they must be nontoxic, able to cross biological barriers able to circulate in the body for the time needed to have a clinical effect [7-8].

**A. High permeability:** It can cross the blood brain barrier, cell membrane. Nanometre range and uniformity in size that can enhance their ability to cross cell membrane [9-10].

**B. Sustained effect:** dendrimers can also release the drug in sustained manner [11].

**C. stability:** They demonstrate the good conjugated stability [12].

**D. Solubility:** Most of the dendrimers they display very low solubility [13].

**III. SYNTHESIS OF DENDRIMERS**

Dendrimer synthesis is a quite new field of polymer chemistry defined by regular, highly branched monomers leading to a Monodisperse, tree-like or generational structure. Monodisperse polymers synthesis needs a good synthetic control which is achieved through stepwise reactions, building the dendrimer up one monomer layer, or "generation," at a time. Each dendrimer consists of a core molecule with a dendritic wedge attached to each functional site. The core molecule is referred to as "generation” [14, 15]

**A. Divergent Method:** The dendrimer is assembling to from a multifunctional core, which is extended outward by a sequence of reactions, commonly a Michael addition reaction. Each step of the reaction must be determined to full completion to prevent mistakes in the dendrimer, which can grounds trailing generations (some branches are shorter than the others). Such impurities can collision the functionality and symmetry of the dendrimer, but are tremendously difficult to purify out because the relative size variation between perfect and imperfect dendrimers is very small [16].

**B. Convergent Method:** Dendrimers are constructed from beginning of small molecules that end up at the surface of the sphere, and reactions precede inmost building inward and are eventually attached to a core. This method makes it very much easier to eliminate impurities and shorter twigs along the way, so that the final dendrimer is more mono-disperse. However, dendrimers ended this way are not as large as those made by divergent methods because crowding due to stearic property along the core is restrictive. The convergent growth reaction of dendrimer can show in Figure 2 [17].



**Figure 2: Synthetic approach of dendrimer by divergent and convergent method.**

**IV. CHEMISTRY AND CLASSIFICATION OF DENDRIMERS**

 A generalized structural formula of dendrimers is shown in Figure 3. Starting material represented structurally as -[CH2N(CH2CH2CO)2]2 is ethylenediamine. The functionality of core Nc is 4, the functionality of branched function Nb is 2. G is the number of generations surrounding the central core and the repeating units [NHCH2CH2N(CH2CH2)]. Z represents the terminal functional groups, which dendrimers are -OCH3 or –NHCH2 NH2 [18].



**Figure 3: A generalized structural formula of dendrimers.**

Dendrimers can be divided into the following categories based on their form, end functional groups, and interior cavities is being shown in Table 1.

**Table 1: Classification of Dendrimer.**

|  |  |  |  |
| --- | --- | --- | --- |
| S. No. | Chemical Classification | Physical Classification | Miscellaneous |
| 1. | Polyamidoamine (PAMAM) dendrimers. | Simple dendrimer | Dendrophanes |
| 2. | Polypropylenemine (PPI)Dendrimers. | Liquid crystalline dendrimer. | Metallodendrimers |
| 3. | Polyether (PE) dendrimers | Chiral dendrimer | Polyaminophosphine |
| 4. | L-lysine based Dendrimers | Micellar dendrimers | Dendritic box |
| 5. | Phenyl acetylene dendrimers. | Hybrid dendrimers | Carbohydrate vaccine dendrimers |

**A. Polyamidoamine dendrimer:** Polyamidoamine (PAMAM) dendrimers are a specific type of dendrimer that consists of a central core, interior branches, and an exterior surface. They are synthesized through a stepwise reaction process, resulting in a well-defined and highly branched polymer structure [19, 20].



**B. Polypropylenimine (PPI):** dendrimers are another type of dendrimer that have gained significant attention in various fields due to their unique properties. PPI dendrimers are synthesized from polypropylenimine, a branched polymer with primary amine groups. Here are some key characteristics and applications of PPI dendrimers [21].



**C. Polyether (PE) dendrimers:** New highly branched poly(ether ether ketone) dendrimers were synthesized by the divergent approach through aromatic nucleophilic substitution reactions. 3,5-Dimethoxy-4'-(4-fluorobenzoyl)diphenylether,1 and 1,3,5-tris[p-(3,5-dihydroxyphenoxy)phenyl)benzene, GO-OH, were used as a building block and starting core, respectively. The reaction of 1 with GO-OH gave the first-generation dendrimer (Gl-OMe), which possessed 12 methoxy groups on the periphery. After the methoxy groups were converted to hydroxy groups by treatment with pyridine hydrochloride, the resultant phenol functionality (GI-OH) was allowed to react with 1 to yield the second-generation dendrimer (G2-OMe) which possessed 24 methoxy groups. By repeating these procedures G3-O By repeating these procedures G3-OMe dendrimer and G3-OH dendrimer possessing 48 methoxy and hydroxy groups, respectively, on the periphery were obtained [22].



**D. L-lysine based dendrimer:** L-lysine-based dendrimers are a type of dendritic polymer that is synthesized using L-lysine, an essential amino acid. Dendrimers are highly branched, tree-like structures with well-defined and repeating molecular units. They have a central core, interior branches, and an outer shell that can be functionalized with various groups for specific applications. L-lysine-based dendrimers are particularly interesting because L-lysine is a natural amino acid found in proteins and has well-established biocompatibility. This makes these dendrimers attractive for various biomedical applications, including drug delivery, gene delivery, and imaging. The synthesis of L-lysine-based dendrimers involves building layers of L-lysine units around a central core molecule. The repetitive nature of dendrimer synthesis allows for precise control over their size, structure, and surface functionalities. This controlled design is crucial for tailoring dendrimers to specific applications [23].

**V. APPLICATION OF DENDRIMER**

Dendrimers are highly branched, well-defined, nanoscale polymers with a wide range of applications across various fields. Their unique structure and properties make them valuable in areas such as medicine, materials science, catalysis, and electronics. Here are some notable applications of dendrimers-

**A. Gene Delivery:** Dendrimers can also be employed as non-viral vectors for gene therapy. Their surface can be modified to carry DNA or RNA molecules, facilitating their transport into cells and enhancing gene delivery efficiency. Dendrimers offer advantages such as high loading capacity, protection of genetic material, and the ability to control the release of genes [24].

**B. Imaging Agents:** Dendrimers can be functionalized with imaging agents, such as fluorescent dyes or magnetic nanoparticles, to enhance the contrast in medical imaging techniques like magnetic resonance imaging (MRI) or fluorescence imaging. These modified dendrimers can help visualize specific tissues or monitor the biodistribution of drugs [25].

**C. Sensors and Biosensors:** Dendrimers' well-defined structure and functionalize surface make them suitable for sensing applications. They can be tailored to detect specific molecules or ions by incorporating recognition sites into their architecture. Dendrimer-based sensors have been used for environmental monitoring, detection of biomarkers, and medical diagnostics [26].

**D. Catalysis:** Dendrimers with catalytically active groups can be employed as efficient catalysts for various chemical reactions. Their large surface area and precisely controlled structure enable the creation of catalytic sites with high activity and selectivity. Dendrimer-based catalysts have found applications in organic synthesis, fuel cells, and environmental remediation [27].

**E. Optoelectronics:** Dendrimers possess unique electronic and optical properties that make them useful in optoelectronic devices. They can be employed as organic light-emitting diodes (OLEDs), organic solar cells, or photodetectors. Dendrimers offer advantages such as tuneable emission wavelengths, high charge mobility, and ease of processing [28].

**F. Coatings and Adhesives:** Dendrimers can enhance the performance of coatings and adhesives by providing improved adhesion, mechanical strength, and resistance to environmental factors. They can be incorporated into paints, coatings, and adhesives to enhance their properties, such as corrosion resistance, scratch resistance, and anti-fouling capabilities [29].

**G. Drug Delivery**: Dendrimers can be used as carriers for drug molecules. Their precisely controlled size, shape, and surface chemistry allow for targeted delivery of drugs to specific sites in the body. Dendrimers can encapsulate drug molecules within their internal cavities or conjugate them to their surface, improving drug solubility, stability, and bioavailability [30].

**VI. CONCLUSION**

 Dendrimers represent a remarkable class of polymers that have captivated researchers across disciplines due to their precisely controlled architecture and versatile properties. The ability to engineer dendrimers at the molecular level has paved the way for a wide range of applications that capitalize on their unique Dendrimers find extensive use in the field of drug delivery, where their well-defined structure allows for precise encapsulation and controlled release of therapeutic agents. Their multifunctional nature enables the incorporation of targeting moieties, enhancing drug delivery to specific tissues or cells while minimizing side effects. Additionally, dendrimers' tunable surface chemistry facilitates the attachment of imaging agents, enabling real-time tracking of drug distribution within the body. In gene therapy, dendrimers serve as promising vectors for the delivery of genetic material. Their ability to compact and protect nucleic acids, such as DNA and RNA, while enabling controlled release in the cellular environment, holds great potential for treating genetic disorders and various diseases at the molecular level. Dendrimers' applications extend into nanotechnology, where they contribute to the fabrication of nanoscale devices and structures. Their precisely controlled size and shape make them valuable components for building nanoscale assemblies, which have implications in electronics, sensors, and catalysis.

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