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Review

Sustainable alternative in environmental monitoring using carbon nanoparticles as optical probes

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ABSTRACT

Environmental monitoring is getting more important nowadays due to the greater stress faced by the natural environment in the era of urbanisation and industrialisation. To accomplish the task, rapid and reliable analytical probes are essentially needed to perform the monitoring at real time basis with high sensitivity and accuracy. In view of this, analytical probes developed using carbon nanoparticles are one of the latest alternatives that are proven with capability to detect various analytes of the environment. Carbon nanoparticles portray good fluorescence property that enables the integration onto optical sensing transducers. Further engineering via surface functionalization can be performed in the interest to improve the selectivity and sensitivity of the probes. There are several advantages of using carbon nanoparticles and the most significant benefit is the sustainability prospect as compared to other groups of fluorophores. Carbon nanoparticles can be synthesised with greener approach via simple pyrolysis or hydrolysis processes that involve minimum use of toxic or harmful starting precursors, besides able to tap on using renewable resources such as carbon rich agricultural wastes. The synthesis is often performed under mild condition and produces less or no side chemical products. Carbon nanoparticles by nature show low toxicity effect to the environment. This review focuses specifically of the sustainable significances, advantages and achievements in adopting carbon nanoparticles as an alternative for environmental monitoring.

Contents

1. Introduction

The environment is facing greater threat of pollution due to the rapid and continuous urbanisation and industrialisation around the world. Natural resources are intensively exploited with increasing amount of wastes produced along with these

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development activities. For instance, solid wastes production has risen tenfold on an average over the past decade and predicted to double up by the year 2025 as forecasted using the current trend of rate [1,2]. It becomes more challenging with the production of new types of wastes over time. E-waste is one of the example where it was not a problem once before, but turns problematic with the estimated production rate of 20–25 million tonnes per year across the world [3]. Handling of such diverse and huge amounts of waste requires enormous efforts, facilities, expertise, and also financial support. Any flaw in the waste management can end up with the wastes polluting the environment. The risk no longer remains localised, but is a global issue since economic globalisation has enabled the transfer of wastes across borders due to trading activities [4].

Effective environmental monitoring programmes are necessary to ensure that the environment is being constantly monitored for any abnormality or pollution. It serves as warning system for the community to take precautionary measures in minimising the contact with the pollutants, besides allowing fast mitigation to be installed in retarding the sources causing the problems. In addition, the data recorded from the monitoring provides an insight on the dynamic interaction between the environment and the stressors. Such information is useful to predict potential environmental impacts in the future and early policies and management programmes can be installed to avoid the impacts besides building a more sustainable future [5]. Generally, environmental monitoring is a process that involves the identification of selected variables of the environment and subsequently quantifying the variables [6]. It often uses simple analytical probes since they are cheaper in price, easier to handle, cater on-site for real time monitoring, and portable as compared to the laboratory tests using conventional instrument. These probes adopt different working mechanisms depending on the transduction systems used, while optical measurement method is one that has gained comparatively much attentions due to its well-known advantages [7]. Measurement based on fluorescence is a popular one, employing a fluorophore as a sensing receptor to detect a specific analyte by measuring the change in the property of fluorescence due to the interaction.

In setting up a fluorescent probe, the type of fluorophore can be chosen from vast selections including organic dyes, semiconductor quantum dots (Q-dots), and to the most recently discovered carbon nanoparticles (CNPs), sometimes better known as carbon dots or carbon nanodots. Basically, CNPs portray similar physical and optical properties to Q-dots, but having lower toxicity risks, easier to synthesis, better biocompatibility, and more economical to develop. The first reported CNPs were accidentally isolated during the electrophoretic purification of carbon nanotubes derived from arc-discharge soot [8], and since then, different synthesis methods have been reported. There are also reports on greener and cleaner synthesis approaches that cover the use of non-toxic natural starting precursors, produces less side products, reduce usage of chemicals, and having fewer steps in the synthesis procedures [9]. In addition, CNPs can be engineered to achieve better sensitivity and selectivity via surface modification.

This review focuses primarily on efforts taken in leveraging the analytical potentials of CNPs, specifically in the application for environmental monitoring. Basic information of CNPs will not be covered as readers can obtain the details from literatures [10,11]. The emphasis is on revealing the sustainability credits of using CNPs as an alternative fluorescent probe for environmental monitoring as compared to probes developed using other classes of fluorophores. This includes the choice of precursors, synthesis approaches, and impacts of such development. It follows by the technical and practical aspects of translating the optically unique CNPs into working analytical probes. The review also covers some significant examples on the successful applications of CNPs in recording and detecting environmental variables of interest. Finally, some outlooks and potential further developments in this area are highlighted.

2. Sustainable options of CNPs

CNPs offer the option for a greener and cleaner fluorophore. This not only refer to its nature that is of low toxicity and better biocompatibility, but covering a wide spectrum stretching from green chemistry synthesis right to the disposal that is environmental friendly. CNPs can adopt various synthesis alternatives [12] and selection can be made from those that comply most of the definitions suggested under the green chemistry principles [13]. These basically cover the use of non-toxic ingredients for the synthesis, generation of less side products, and apply of mild synthesis condition.

2.1. Non-toxic starting precursors

CNPs consist of majority carbon, an element that is widely abundance in the nature and readily obtainable. This gives the option to synthesis CNPs from wide selections of carbon-rich starting precursors, favouring to those containing less harmful elements. For instance, carbohydrates from plants serve to produce CNPs that are safer as compared to hydrocarbons from petroleum that may contain contaminants such as lead or sulphur. The selection starting precursor is far more flexible as compared to the Q-dots that are made mostly of toxic precursors with risks of leaching during the application [14]. Besides, CNPs can be produced from sustainable renewable resources.

CNPs can be produced from fine carbon-rich chemicals that are readily obtainable from the market. These can be of small organic molecules or huge macromolecules in high purity form. For instance, Qu et al. [15] have reported the use of dopamine; a catecholamine neurotransmitters in the mammalian central nervous system to prepare the CNPs. The risk in toxicity is low since none of the ingredients are harmful to biological systems or the environment. Other similar attempts were reported to use ascorbic acid [16,17], amino acid [18], citric acid [19,20], lactose [21], sucrose [22], which are all of low toxicity risk. Larger molecules such as proteins and polymers can also be converted into CNPs. For example, bovine serum albumin (BSA), a protein with molecular weight of 66.5 kDa can be converted into CNPs that will emit blue fluorescence [23,24]. Besides protein, polymeric compounds such as commercial gelatine and polyethylene glycol can also produce CNPs with good fluorescence property [25,26].

Another alternative of the starting precursor is the direct use of crude natural products. It can be sourced from plants or poultry related products with minimal effort in purification. Edible chicken egg for instance can be converted directly into highly fluorescent CNPs using a single step plasma-induced pyrolysis [27]. No chemical pre-treatment or compound extraction of the egg is required, but only a simple separation of the yolk from the white before the synthesis. Although from a more complex matrix, the isolated CNPs showed no great difference in terms of the basic optical property or the physical morphology. Similarly, orange juice free of pulp can be treated hydrothermally to produce CNPs [28]. Other examples of crude natural products that can produce CNPs are such as bamboo leaves [29], soya milk [30], microalgae [31], and honey [32].

The direct use of agricultural wastes can be another option of starting precursor. This category of precursor is often cheap and readily available. The wastes are basically the left over after harvesting of useful crops such as fruit peels, cereal husks, straws, leaves, or tree trunks, which have no other uses. Normally the