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Review

Progress and recent advances in phosphate sensors: A review

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ABSTRACT

This review covers the progress made in the development of sensors for inorganic and organic phosphates that are significant pollutants within the environmental and biological systems. Phosphate sensors in the forms of amperometric, potentiometric enzyme electrodes, plant tissue electrode and screen printed electrode are described. Instrumental probes such as fluorescence, chemiluminescence, luminescence and potentiometric ion selective electrodes are also described. Recent efforts on the use of voltammetric, potentiometric and amperometric biosensors for the determination of phosphate are highlighted.

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1. Introduction

1.1. Significance of phosphate

Phosphate is a well-known contaminant of ground and surface water, and it is one of the two substances that have been implicated in the frequent eutrophication of lakes and coastal waterways, the other being nitrate [1–5]. Owing to its nature, it can be present as inorganic and/or organic phosphorus. Phosphates are generally grouped into three main classes. They are orthophosphate, condensed phosphate (which consist of pyre-, meta-, and polyphosphate) and inorganic phosphorus [6]. The largest single source of inorganic phosphorus is synthetic detergent, while food and human wastes are the major sources of organic phosphorus [1,2,4,7]. Through biological action in the environment, all phosphorus are eventually converted to the inorganic forms. Despite the various attempts that have been made in recent years to encourage the use of phosphate-free detergent and to minimise the use of phosphate fertilisers, very high concentrations of phosphate are still often found in natural waters and sediments [3,4,8]. Processes such as wind erosion, surface runoff and leaching are the main pathways for transport of phosphorus from terrestrial to aquatic ecosystems. The discharges from these processes are further accelerated by agriculture, animal husbandry and other anthropogenic activities. These various sources result in increasing levels of phosphate and the eutrophication of lakes and coastal water [9,10]. Keup [11] observed that increasing the phosphate concentration in a body of water also caused accelerated growth of plankton, which made such water unsuitable for drinking.

Phosphorus is also an essential nutrient for all plants and it is normally absorbed via the roots. In modern agriculture, phosphorus is supplied to crops as fertiliser. Commercial phosphorus is manufactured from phosphate rock, which is mined in various locations throughout the world. However, there has been some concern that the phosphate rock reserve is being rapidly depleted as a result of its increasing use. According to a recent estimate, the current reserve is expected to last for less than 100 years [9,12].

The presence of phosphate in drinking water is another area of concern. Consequently, the determination and control of phosphate in natural water sources is a high priority for maintaining good water quality. The maximum permissible concentration of phosphate in drinking water recommended by the World Health Organisation is 1 mg L^{-1}. In Australia the maximum permissible level of phosphate in drinking water is 0.046 mg L^{-1} [13].

Phosphate measurements are also important for clinical diagnosis of various disorders. The diagnosis of hyperparathyroidism, hypertension [14], vitamin D deficiency, mineral and bone disorder [15] and Franconia syndrome [16,17] is some of the clinical conditions where the determination of phosphate concentrations in body fluids is necessary. The determination of phosphate levels in body fluids can also provide useful information about several diseases such as kidney failure [15]. The adverse effects of abnormally elevated blood level of phosphate (hyperphosphatemia) such as calcium phosphate deposition can lead to kidney damage The energetic state of the cell and bone function because phosphate salts are known to provide mechanical rigidity to bones and teeth [12,14,15,18]. Phosphate activities in the body organs include intestinal absorption of phosphate from the diet, release of phosphate through bone resorption, and renal phosphate excretion [19]. Khoshiniat et al. reviewed the data that phosphate sensing mechanism may be present in various organs and such sensor will detect changes in serum or local phosphate concentration. This suggest that phosphate is a signal regulating biological process such as bone or vascular calcification [18]. Phosphate is a well known genetic component of cells responsible for the production of proteins in living systems. Adenosine triphosphate (ATP) in cells has recently been analysed by Chen et al. [20], thus, phosphate ions and its derivatives thus play an important role in energy and signal transduction [21–23]. Shervendani and Pourbeyaran [24] monitored phosphate in blood serum for phosphate management in CKD-related mineral and bone disorder.

Millions of dollars are also spent on wastewater treatment to remove phosphate from water prior to disposal [9,25]. For these reasons the monitoring of phosphate concentration is very important for maintaining good water quality and minimising pollution of natural waters. Fast, simple and sensitive methods for measuring phosphate concentrations are required to enable rapid assessment of phosphate in various systems. This review examined the developing strategies in the various fabrication methods of sensitive and selective biosensors for rapid determination of phosphate in natural waters and to compare the merits and limitation of other recent competing techniques. This review is divided into four major parts: the first part which deals with the introduction, the second part deals with methods of phosphate determination, the third parts deals with biosensor and phosphate biosensor and the fourth part is other techniques of phosphate sensing. The aim of this review is to provide an update on work on phosphate which has been published in the period from 1970 to 2012 and targeted mainly at researchers who are active in the field of phosphate sensing.

2. Methods of phosphate determination

2.1. Classical methods

Classical analytical methods commonly employed for routine determination of phosphate are gravimetric methods (phosphate precipitated as magnesium pyrophosphate, magnesium ammonium phosphate hexahydrate), volumetric methods (by titration of ammonium phosphomolybdate with sodium hydroxide) and classical instrumental method based on spectrophotometric and chromatographic measurements [26–35], but these techniques require sample pre-treatment that can be time consuming, expensive and produce toxic wastes. Due to poor sensitivity of classical methods, most samples after dissolution are analysed by means of instrumental methods. Most commonly, phosphate determination is based on the molybdenum blue method of Fiske and Subbarow [34], which are both complicated and time consuming. Nakamura et al. compared this method with a phosphate biosensor method and found that as a result of acidification of sample in molybdenum blue method, biosensor methods are less complex and more sensitive.

The methods commonly employed for determination of phosphate in natural waters include colorimetry [37–45], ion chromatography