G Model
JIEC 3629 No. of Pages 10

ARTICLE IN PRESS

Journal of Industrial and Engineering Chemistry xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Industrial and Engineering Chemistry

journal homepage: www.elsevier.com/locate/jiec

Review

Creating functional water by treating excited gold nanoparticles for the applications of green chemistry, energy and medicine: A review

Hsiao-Chien Chen, Yu-Chuan Liu*

Department of Biochemistry and Molecular Cell Biology, School of Medicine, College of Medicine, Taipei Medical University, 250 Wuxing St., Taipei 11031, Taiwan

ARTICLE INFO

Article history:
Received 20 June 2017
Received in revised form 15 August 2017
Accepted 12 September 2017
Available online xxx

Keywords:
Hydrogen bond
Plasmon-activated water
Gold nanoparticles
Antioxidant
Green energy

ABSTRACT

The strength of hydrogen bonds (HBs) decides water's properties and activities. It is recognized that the properties of confined liquid water, or liquid water in contact with hydrophobic surfaces, significantly differ from those of bulk liquid water. However, these unique properties of water are only found within the interfacial phase and a confined environment; thus, their applications are limited. Nowadays, environmentally friendly science, health and energy are main concerns in the world. In this review, an innovative and facile method for preparing mass-produced plasmon-activated water (PAW) with reduced HBs by letting bulk water flow through gold-supported nanoparticles (AuNPs) under resonant illumination at constant temperature is reported. The resulting stable PAW exhibits distinct properties and activities, which significantly differ from those of untreated bulk water. In addition, this PAW has the obvious advantages in environmentally friendly science, green energy, water saving and medicine.

Contents

Introduction

Water molecules are the most abundant compounds on earth. They have multiple functions in chemical and biological reactions, global climate, and so on [1–3]. Water is the most important necessity in our daily lives. The specific chemical formula, H_2O,

* Corresponding author.
E-mail address: liuyc@tmu.edu.tw (Y.-C. Liu).

http://dx.doi.org/10.1016/j.jiec.2017.09.026

Please cite this article in press as: H.-C. Chen, Y.-C. Liu, Creating functional water by treating excited gold nanoparticles for the applications of green chemistry, energy and medicine: A review, J. Ind. Eng. Chem. (2017), http://dx.doi.org/10.1016/j.jiec.2017.09.026

provides two donors from an oxygen atom and two acceptors from hydrogen atoms to form hydrogen bonds (HBs) with surrounding water molecules. The different strengths of network interactions result in the presence of gas, liquid, and solid phases in the common atmosphere. In particular, liquid water is inseparable from human life and is closely related. Generally, HBs within homogeneous liquid water construct predominantly tetrahedral coordination with other broken HBs [4]. This intermolecular network interaction within water molecules exhibits anomalous properties in terms of dynamic and thermodynamic behaviors [5,6]. The water covering 71% of the earth's surface is considered a major factor in climate regulation due to its high heat capacity. Water is a polar with non-uniform electronegativity and the ability to form HBs, which make it an excellent solvent for some salts and hydrophilic components. In catalytic reactions, for instance, water is used as a catalyst to decompose formic acid to carbon dioxide and hydrogen and to oxidize chromopyrrolic acid by cytochrome P450 StaP [7,8]. It also plays an essential role in all living entities and functions as a solvent. In the human body, water plays roles of a medium for nutrient transfer and a carrier for species and stabilizing the body temperature. Additionally, water participates in some biochemical reactions such as hydrolysis [9,10], glycogen decomposition, and adenosine triphosphate (ATP) decomposition [11,12].

However, these "usual" properties of water can be changed by the effects of temperature [13,14], solutes [15–18], external fields, and the environment that are associated with the strength of HBs [19]. It is well known that water's HBs can be destroyed by raising the temperature or adding salt ions. The evidence for weakening of the external magnetic field according the strength of HBs was provided by spectra [20]. Water's refractive index, viscosity, and electric conductivity dramatically increase in the presence of a magnetic field [19,21]. Although the detailed mechanism is still a mystery, magnetized water exhibits some practical applications in cleaning [22,23], biology, and health [24–27]. Engineered water produced from electrospraying water vapor features reactive oxygen species (ROS) that can inactivate foodborne microorganisms [28]. It can be applied in the food industry as a green alternative to existing disinfection methods [29,30]. In addition, water's orientation and HBs are also changed when it is confined in a nano-sized environment or is at an interface [31–36]. The chemical and dynamic properties of water in an interface differ from those of bulk water. HBs of water are shorted on the interface by titanium dioxide (TiO_2) due to electronic charge transfer [37]. The dangling (non-hydrogen-bonded) OH groups are found at the oil/water or hydrophobic species/water interface, which are favorable for improving some chemical reactions [35,38–40]. An increase in dipole–dipole interactions with a decrease in the strength of HBs was detected when water was confined in nano-sized pores or channels such as nanotubes and beryl [41,42]. However, these unique conformations and properties are only characterized by simulated calculations because it reverts instantly to a normal state of bulk water when it departs from an interface or nano-sized environments.

Additionally, water with some special functions was developed for further applications. The most watched research is hydrogen-rich water which is a useful hydroxyl radical scavenger that efficiently reduces oxidative damage [43]. It also ameliorates bronchopulmonary dysplasia [44], improves neurological functional recovery [45], attenuates amyloid β-induced cytotoxicity and prevents progression of nonalcoholic steatohepatitis [46,47]. Acidic cosmetic water acts against *Staphylococcus aureus*, has anti-inflammatory properties, and is a superoxide anion radical scavenger [48]. Sulfurous water has an antioxidative function [49]. However, these waters are not pure waters. Their special functions are attributed to additional additives such as hydrogen gas and minerals.

Recently, we proposed a novel functional water, plasmon-activated water (PAW), which is produced by treating deionized (DI) water with excited gold nanoparticles (AuNPs) [50–59]. This PAW without additives exhibits a low specific heat and boiling point [56], high vapor pressure and osmosis [50], efficient antioxidant and anti-inflammatory properties [50,51], and high solubility and diffusion to solutes [50,51,52]. Based on these specific properties, PAW can be the source of green energy for improving the efficiencies of hydrogen and oxygen production when splitting water [52,54,58]. For green chemistry, PAW is used as a reductant for reducing gold and silver ions [51,56]. It extracts greater amounts of nutrients from tea leaves and *Polygonum multiflorum* (PM) [55]. The vapor from PAW is an environmentally friendly etchant for modifying surfaces of glass and wafers [57]. Its property of enhancing solute diffusion significantly shortens the time to remove uremic toxins during hemodialysis (HD) treatment [51,59]. In the meantime, it decreased fibronectin expression and attenuated renal fibrosis in a chronic kidney disease (CKD) mouse model [59]. In addition, ongoing experiments indicate that PAW possesses highly potential strategies for therapies of lung cancer, liver damage during chronic sleep deprivation (SD), and Alzheimer's disease. Descriptions related to PAW's creation mechanism, spectral characteristics, special properties, and potential applications are introduced in this review based on ten published papers by our group [50–59].

Creation and characteristics of PAW

The creation mechanism of PAW

In addition to temperature and dissolved salts, network interactions within water molecules can be disturbed by electron or charge transfer. At the interface of TiO_2/water, an excess electronic charge on the mineral surface is transferred to oxygen atoms through a pair of water molecules, resulting in a rearrangement of the electronic charge and shortening of HBs at the interface [37]. Santos et al. reported that water dropping from a biased metal needle can acquire an electric charge [60]. The charge of water (negative or positive) depends on the applied potential. Also, a positive charge was observed when heating water [61]. Moreover, the electrospray process enhances the surface charge of water vapor [28]. These results reveal that electrons are present and stable in water. Lately, creating PAW with a negative charge has been proposed [56,57]. The equipment to produce PAW is constructed by AuNP@ceramic powder and light-emitting diodes (LEDs) at a wavelength of 532 nm (Fig. 1A) [54]. Also, the creation mechanism of PAW was proposed based on illumination of AuNP@ceramic powder (Fig. 1B) [56]. In this process, hot electrons generated from the decay of excited AuNPs are injected into bulk water to affect HBs within water molecules *via* two pathways, breaking and occupation. For the breaking pathway, accumulating sufficient energy from hot electrons to destroy HBs is necessary. On the other hand, hot electrons can directly occupy short-lived vacancies due to the spontaneous rearrangement of HBs in the picosecond scale. In addition, Au L_{III}-edge X-ray absorption near edge structure (XANES) spectra demonstrated that hot electrons are injected into DI water to form PAW (Fig. 1C) [56]. The injected hot electrons from AuNPs to DI water through two pathways resulted in the generation of charged PAW (-31.2 ± 0.70 mV) [56]. This metastable PAW can persist for about 7 days at room temperature in a closed system. Furthermore, PAW is more sensitive than electrically neutral DI water in an electric field due to the charge effect [57].