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Research Paper

Effect of process variables on ethylene removal by vacuum ultraviolet radiation: Application in fresh produce storage

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Detrimental effects of ethylene on fresh produce make ethylene removal one of the major challenges in storage of horticultural commodities. Novel techniques based on advanced oxidation processes such as photocatalysis and photolysis by vacuum ultraviolet light (VUV) offer good potential for ethylene removal. This study focused on the use of VUV photolysis and the impact of different process variables on the efficiency of this technique. The set objectives of this study were to investigate the combined effects of three process variables; flow rate, initial ethylene concentration, and ultraviolet radiation on the efficiency of VUV photolysis for removal of ethylene at normal atmospheric conditions. Response surface methodology along with Box–Behnken design was applied to determine the combined effect of these variables. Flowrate exerted the most significant effect on the amount of ethylene removed, followed by initial ethylene concentration and ultraviolet lamp power. The combined effect of these three process parameters exerted a significant effect on percentage ethylene removal. Reducing the flowrate and increasing the lamp power as well as the initial ethylene concentration had a positive effect on the amount of ethylene removed. For an initial ethylene concentration of 5 ppm, the percentage ethylene removal (76%) was highest under optimised process variable of 9 W lamp power and 0.5 L/min flowrate. The developed reactor was tested on short term storage of apples and kiwifruit. The reactor effectively reduced ethylene concentrations in storage space of both products. Kiwifruit storage connected to the reactor had higher flesh firmness compared to the control samples.

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1. Introduction

Ethylene is a colourless and odourless gas that is naturally produced as a by-product of plant metabolism, and it is also generated during burning of hydrocarbons (Zagory, 1995). It is a plant hormone that plays an important role in the growth and development of fruit and vegetables (Saltveit, 1999). Besides its beneficial effects, ethylene also exerts numerous negative impacts on fruit and vegetables with the most prominent being accelerated ripening and rapid decay of fresh horticultural produce (Mahajan, Caleb, Singh, Watkins, & Geyer, 2014; Saltveit, 1999; Wills, Warton, Mussa, & Chew, 2001). It is estimated that 10–30% of fresh produce is wasted because of undesired ethylene exposure (Warton, Wills, & Ku, 2000). Thus, the removal of ethylene from storage systems is one of the major postharvest challenges in the horticultural industry.

Common methods for removing ethylene in horticultural space involve the use of adsorbers and oxidisers (Arteca, 2014). These methods have several limitations in terms of absorption capacity, the need for continuous replacement and/or additional disposal challenges. Catalytic oxidisers promote oxidation of ethylene in presence of a catalyst at high temperatures, thus, offering better application in terms of continuous ethylene removal, no by-product disposal limitation and no frequent replacement. However, high initial capital and operational cost due to energy consumption are limiting factor for this method. Alternatively, ultraviolet light based equipment/reactors which have lower energy requirement can be used, as they can operate at room temperatures (Huang et al., 2016). The photocatalytic oxidation (PCO) technique based on UV light is an emerging technique that involves the use of a catalyst (e.g. TiO_2, ZnO, ZnS, CdS, Fe_2O_3, SnO_2) and UV light (normally ranged between 200 and 380 nm depending on the catalyst).

These techniques have been extensively researched for removal of volatile organic compounds in indoor air purification (Huang et al., 2016; Zhao & Yang, 2003) as well as for oxidation of ethylene (Keller, Ducamp, Robert, & Keller, 2013; Pathak et al., 2017). PCO involves irradiation of a catalyst, such as titanium dioxide by ultraviolet light. The process generates electron–hole pairs at the surface of the catalyst that react with surface adsorbed oxygen and water to produce reactive oxygen species (such as hydroxyl radicals, $OH^{\bullet}$ and superoxide ions, $^{\cdot}O_2^-$) that eventually oxidises ethylene to carbon dioxide and water. This is a cost effective technique that can operate at room temperature and pressure. Literature concerning the utility of PCO for ethylene removal in fresh produce storage is emerging (de Chiara, Pal, Licciulli, Amodio, & Colelli, 2015; Hussain, Bensaid, Geobaldo, Saracco, & Russo, 2011; Kartheuser & Boonaert, 2007; Maneerat & Hayata, 2006; Nielsen, Vesborg, Hansen, & Chorkendorff, 2015). However, this method suffers from catalyst deactivation due to accumulation of intermediate products at catalyst surface and low efficiency due to electron–hole pair recombination (Huang, Leung, Li, Leung, & Fu, 2011). Moreover, at high humidity the ethylene removal efficiency decreases due to the competing effect between water and ethylene molecules to get adsorbed on the catalyst surface (Jeong et al., 2013).

Photolysis based on vacuum ultraviolet (VUV) light, unlike PCO, does not involve the use of a catalyst, instead the VUV irradiation (wavelength < 200 nm) has high energy photons that are self-sufficient in dissociating oxygen and water present in the gaseous state to produce reactive species such as atomic oxygen $O(^1D)$, $O(^3P)$, hydroxyl radicals ($^{\bullet}OH$) and ozone (O_3) which oxidise ethylene (Huang et al., 2016). VUV photolysis has a higher overall efficiency than PCO as photocatalysis is a surface phenomenon occurring on the surface of the catalyst whereas the photolysis occurs in the gas phase and therefore is faster and consequently has a higher efficiency. In a study on toluene removal (Hussain, Russo, & Saracco, 2011), 63.9% removal efficiency was reported with VUV photolysis alone as compared to 14.3% in case of PCO. Unlike PCO, VUV photolytic effect is not diminished at high humidity as water molecules are converted to hydroxyl radicals which are strong oxidising species. In the same study by Hussain, Russo, et al. (2011), toluene removal was observed to be higher in wet air than dry air with the efficiency of removal being 63.9% and 43.3% in respective cases.

Very few studies on the application of VUV on ethylene removal have been reported especially those relating to application in fruit and vegetable storage. The main motivation for this study was to develop an efficient VUV based process for ethylene removal for application in fruit and vegetable storage. In early 70s and 80s, some studies on the application of VUV light on ethylene were reported (Scott & Wills, 1973; Scott, Wills, & Patterson, 1971; Shorter & Scott, 1986). The potential of VUV in ethylene removal for the purpose of fruit storage was demonstrated by Scott et al. (1971). Shorter and Scott (1986) experimented on removal of ethylene using VUV producing lamps at different oxygen concentrations. In those studies, the actual oxidation mechanism was not known; however, atomic O_2 was proposed to be responsible for the effect. These studies presented the potential of this technique for application in horticultural storage industries, but did not provide the details of mechanism and guidelines for development of an efficient system. For potential application in controlled atmosphere (CA) storage of apples, a static model was developed by Jozwiak, Bartsch, and Aneshansley (2003). In that study, the authors mainly focused on the effect of O_2 concentration on ethylene removal in presence of VUV light but did not cover the effect of other engineering and process parameters that influence photo-oxidation. Key parameters affecting the photo-oxidation of ethylene include flow rate, the light intensity, feed composition (ethylene, oxygen, and water concentration), and temperature (Lin, Weng, & Chen, 2014; Obee & Hay, 1997). In order to develop a highly efficient ethylene removal process it is important to take into consideration the combined effect of these factors.

Thus, this study was aimed at investigating the combined effects of flow rate, initial ethylene concentration, and UV radiation in VUV photolysis for removal of ethylene at normal atmospheric conditions. For process optimisation, response surface methodology was implemented. Box–Behnken (BB) design with three factors (flow rate, lamp power, and initial ethylene concentration) and 3-levels was applied. The model developed was experimentally validated. The optimised

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