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King of Spices in Cold Plasma Immersion *– A potential microbial decontamination technology*

Production

Sri Lanka is home to the king of spices – Pepper and also Sri Lanka earned its historical moniker as the "Spice Island" due to its geographical advantage, boasting a tropical climate that enhances the flavors of its spices, making them prized in the global market. Annual black pepper production in 2020 was 23,970 MT. Exports of black pepper valued 49.18 US$ Million in 2020 hold a significant share of the spice export market in Sri Lanka [1]. Other competitive black pepper producers are India, Indonesia, Malaysia, and Vietnam [2]. Fig.1 (a and b) shows the black pepper cultivation areas in Sri Lanka and the major export destinations. Black pepper seeds, rich in piperine and essential oils, are valued for their pungency and health benefits. The composition of volatile oils and piperine content depends on maturity, with Sri Lankan black pepper containing 8.6 ml/100g and 11.5 ml/100g at 22.5 weeks of maturity [3].

Figure 1: Black pepper cultivation in Sri Lanka (a) and major export destinations (b)

Processing

Green pepper is harvested at the age of 6 – 8 months and processed to produce black pepper following drastically different methodologies depending upon the factory's investment level, expected hygienic levels, and quality standards of the final product. Many industries purchase black peppers and complete the processing steps in-house. After buying dried seeds, they wash them with potable water and then dry them again to eliminate absorbed and surface water. Some medium-scale industries, prioritizing product quality, use steam sterilization with wet steam to deactivate Salmonella. However, wet steam can moisten the product again, so further drying is needed for better shelf stability. Producing black pepper powder involves coarse grinding, fine grinding, and sieving to achieve different grades of powder. Poor hygiene during processing, especially in rural spice industries lacking Good Manufacturing Practices (GMP) and Good Hygienic Practices (GHP), contributes significantly to microbial contamination risks.

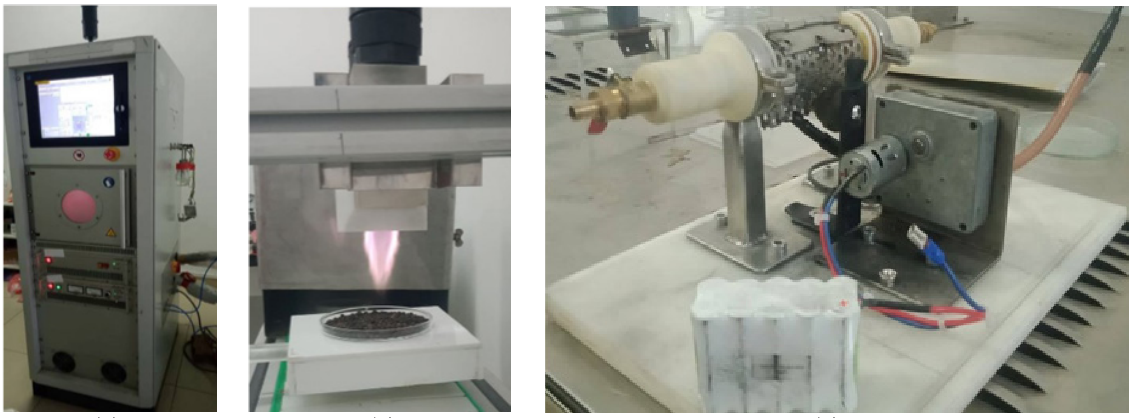
Preservation and Global Quality Concerns

Drying plays a crucial role in black pepper processing, with methods like sun drying, solar drying, and hot air drying being common in industrial settings. Sun drying, although cost-effective, can take up to 20 days to reduce moisture content to 10-15%, posing contamination risks during prolonged exposure. Even hot air drying, while faster, can lead to contamination in high moisture and dust environments with poor air quality, especially during extended low-temperature drying periods [14]. According to the Food and Agriculture Organization of the United Nations, 25-30 % of the crops are susceptible to mycotoxin formation throughout the supply chain [4]. Aflatoxin is one of the key global issues in supply chains due to its toxic, teratogenic, mutagenic, and carcinogenic properties. Microbiological standards are vital in the spice trade, varying by country or region. The efficacy of Cold Plasma technology as a potent sterilization technology is experimented globally with the drawbacks encountered in both thermal (dry and wet steam, hot air) and non-thermal (gamma irradiation, fumigation, and UV irradiation) sterilization technologies.

Cold Plasma (CP) Technology

With the drawbacks of conventional thermal sterilization methodologies, it is necessary to establish non-thermal sterilization technologies. Technologies in which the heat is not involved, for example gamma irradiation, UV processing, fumigation, and ozonation are used in commercial operations. High-pressure processing, pulsed light, and infrared irradiation are still less standard in industrial operations.

Plasma can be generated by ionizing a gas using various energy sources such as mechanical, thermal, nuclear, radiant, or electric currents. It exists across a wide range of temperatures and pressures, formed by coupling energy to a gaseous medium [5]. Plasma consists of excited atomic, molecular, ionic, and radical species alongside reactive elements like electrons, ions, free radicals, and gas molecules. Additionally, plasma emits electromagnetic radiation in the form of UV photons and visible light [6].



(a) (b) (c)

Figure 2: Schematic diagrams of Low-Pressure CP (a) LPCP and (b) GAPD (c) The new reactor prototype

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Tested Plasma Models

The different CP setups: Low Pressure Cold Plasma (LPCP) and Gliding Arc Plasma Discharge (GAPD) used in the research are as below in Fig. 2 (a) and (b). The comparative advantages and disadvantages of treating black pepper seeds in LPCP and GAPD were evaluated [5].

The Low-Pressure Cold Plasma (LPCP) method employs a high-frequency (Radio Frequency, RF, at 13.56 MHz), while the Gliding Arc Discharge (GAPD) technique utilizes high voltage (15 kV). Comparing the two, LPCP demonstrated more effective microbial inactivation than GAPD. However, LPCP's widespread adoption is hindered by its high initial and operational costs. On the other hand, GAPD faced challenges such as reduced inactivation efficacy in remote areas and a notable temperature rise during treatment, peaking at 65.2°C after 15 minutes to proceed as a non-thermal technology. Additionally, shield and shadow effects contributed to lower microbial inactivation rates. Given the importance of preserving physicochemical properties during the decontamination of black pepper seeds using CP technology, achieving optimal microbial inactivation levels becomes imperative. These insights led to the conceptualization of a RF-powered rotary CP reactor designed specifically for decontaminating black pepper seeds.

A novel CP reactor for microbial decontamination of black pepper seeds

Ensuring optimal inactivation levels while minimizing alterations to physicochemical properties is paramount during the decontamination of black pepper seeds using CP technology. To address concerns raised by treatments like LPCP and GAPD, a conceptual design for a novel CP reactor was developed, culminating in the fabrication of a prototype reactor (Fig. 2 (c)).

The reactor's performance was assessed using natural bacteria and fungi contaminations. It demonstrated effective microbial inactivation while maintaining the integrity of physicochemical and sensory properties. Ongoing enhancements to the reactor are underway, with potential for scalability as a batch or continuous system. This advancement could pave the way for establishing a minimal processing technology to enhance the quality of black pepper seeds.

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