

PLASMAFOOD: A physics-based hybrid energy system innovation for portable cold plasma generation as a non-thermal food security solution

Della Puspita^{1*}, Winnie Marvella²

¹Department of Physics, Universitas Riau, Pekanbaru 28293, Indonesia

²Department of Chemistry, Universitas Riau, Pekanbaru 28293, Indonesia

*Corresponding author: della.puspita0017@student.unri.ac.id

ABSTRACT

Global food security faces significant challenges due to high post-harvest losses, limited energy access, and inadequate cold chain infrastructure, particularly in rural and remote areas. Cold plasma technology has been proved effective in inactivating microorganisms by up to 99% and extending food shelf life without compromising its physical and sensory qualities. However, its implementation remains limited to laboratory and industrial scales due to dependence on conventional electrical energy sources and non-portable system designs. This study aims to develop PLASMAFOOD, an portable cold plasma system based on hybrid renewable energy by integrating photovoltaic, thermoelectric, and piezoelectric sources to provide an independent energy supply. The system is designed that operated at low power (15 – 25 W) with high voltage (10 – 15 kV) to generate plasma suitable for food sterilization. The results indicate that the integration of hybrid energy improves system efficiency and operational stability while enabling implementation in off-grid areas. Therefore, this study contributes to bridging the gap between the potential and practical application of cold plasma technology, as well as supporting the development of sustainable, energy efficient, and environmentally friendly food systems.

Keywords: Energy; food; plasma; sterilization; sustainable

Received 13-02-2026 | Revised 20-03-2026 | Accepted 27-03-2026 | Published 31-03-2026

INTRODUCTION

The global food security crisis is becoming increasingly evident amid climate change, energy limitations, and unequal distribution of agricultural products. A report by the Food and Agriculture Organization (FAO) estimates that more than 30% of the world's harvest is wasted each year due to post-harvest losses, inadequate storage, and the lack of cold chain infrastructure in rural areas [1]. This highlights structural weaknesses in food preservation systems in developing countries, including Indonesia, which has high agricultural production but limited storage infrastructure. On the other hand, the electrical energy required for conventional cooling systems such as refrigerators and cold storage remains relatively high, while many remote agricultural regions still lack access to stable electricity [2]. These challenges demand new approaches

capable of preserving food with low energy consumption, without heavy reliance on refrigeration, while remaining environmentally friendly.

Along with advancements in physics and materials engineering, innovations based on cold plasma have emerged as a non-thermal technology capable of inactivating microorganisms that cause spoilage without heating food products. Cold plasma is formed when a gas is subjected to high voltage until it becomes partially ionized, producing a mixture of reactive oxygen and nitrogen species (ROS and RNS) such as O₃, O⁻, and NO-which are effective in damaging microbial cell walls and DNA [3]. Unlike pasteurization or thermal sterilization methods, cold plasma does not alter the texture, color, or taste of food products. This makes it a promising preservation technology with significant potential for fresh products, especially in areas that lack

refrigeration facilities. Recent studies have shown that the use of plasma-activated gas and plasma-activated water (PAW) can significantly extend the shelf life of various agricultural commodities. A study by Song et al. (2025) found that treatment with plasma-activated water on fresh mangoes was able to suppress microbial growth by up to 99% and maintain sensory quality for more than a week at room temperature [4]. The combination of plasma-activated water with natural compounds such as tannic acid can enhance color stability and inhibit oxidation in postharvest strawberries.

With such high effectiveness and treatment times of only a few minutes, cold plasma has the potential to serve as a substitute for energy-intensive that refrigeration, particularly in smallholder agricultural sectors [5]. However, the main limitation of this technology is the initial energy required to generate plasma. Although the required power is relatively low (around 30 – 50 W), dependence on AC electricity remains a barrier to its implementation in rural areas.

Therefore, the integration of renewable energy becomes a crucial step to ensure that this innovation is truly sustainable. The concept of a hybrid system based on photovoltaic, thermoelectric, and piezoelectric energy offers an attractive solution. Solar energy can serve as the primary source, while ambient heat and vibrations (from wind or equipment activity) can be utilized as complementary sources. This multi-source approach enables the development of portable plasma systems that can operate independently without reliance on external electrical grids, in line with the goals of sustainable development goals.

Indonesia has significant potential to adopt this approach. With abundant sunlight and a large agricultural community, a hybrid-powered portable cold plasma system could become a practical and impactful innovation. In addition to being environmentally friendly, this technology has the potential to reduce postharvest food loss, extend the shelf life of fresh produce by 3 – 5 times, and create new economic opportunities for farming

communities. Furthermore, it can strengthen rural energy independence, expand access to food preservation technologies, and reduce reliance on fossil fuel-based cooling systems.

Thus, the development of a hybrid energy-based portable cold plasma system is not merely a technical innovation, but an integration of physics, chemistry, and renewable energy technologies to address food security challenges. This essay will elaborate on the scientific background, technological design, and potential field applications of this system, while demonstrating how the application of pure physics can directly contribute to food sustainability in Indonesia.

RESEARCH METHODS

The methodology of this research were focuses on the development and operational principles of a portable cold plasma system known as PLASMAFOOD. The fundamental mechanism of this technology is based on the generation of cold plasma, or non-thermal plasma (NTP), which is a gaseous state where a portion of its particles becomes ionized through the application of high electrical voltage.

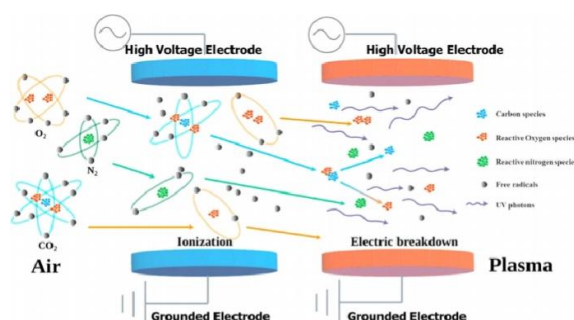


Figure 1. Generation of atmospheric cold plasma through the ionization of gas molecules in an electric field, producing a mixture of electrons and ions [6].

This process creates a complex mixture of ions, electrons, and free radicals. In the specific context of food preservation, air or neutral gas is subjected to high voltage to form a plasma environment that is rich in Reactive Oxygen Species (ROS), including ozone (O_3) hydroxyl (OH), and superoxide (O_2^-), as well as Reactive

Nitrogen Species (RNS) such as nitric oxide (NO) and nitrogen dioxide (NO₂). Physically, the working principle is rooted in the process of ionization, which involves the separation of electrons from atoms or molecules due to exposure to a strong electric field. These fast-moving electrons collide with surrounding gas molecules, generating charged particles and ultraviolet (UV) photons that contribute significantly to antimicrobial activities. A critical physical characteristic of this system is that the kinetic energy of the electrons remains much higher than that of heavier particles like ions and neutral molecules; consequently, the overall gas temperature remains low, which is why the technology is categorized as cold [7].

To address the practical limitations of conventional experimental systems which typically rely on stable AC power and fixed laboratory infrastructure the PLASMAFOOD innovation is designed as a portable unit utilizing a multi-source hybrid energy system. The architecture of this system integrates three distinct renewable energy technologies: photovoltaic, thermoelectric, and piezoelectric, all consolidated into a single functional unit. The photovoltaic panel serves as the primary energy harvester, capturing solar energy and converting it into direct current (DC). This energy is not immediately consumed but is instead directed through a charge controller into a 12 V, 7 Ah Lithium-ion battery for storage. To enhance energy stability, thermoelectric (TEG) modules are strategically placed on the sides of the device that are exposed to solar heat, utilizing the temperature gradient between the sunlit exterior and the ambient environment to produce a small but consistent electrical charge. Furthermore, the system incorporates piezoelectric elements based on zinc oxide (ZnO) or lead zirconate titanate (PZT), which are integrated into the support structure of the device. These elements function by converting mechanical pressure arising from environmental vibrations, wind, or movement during the transportation of goods into supplemental electrical energy [8].

The integration of these three energy mechanisms enables the system to produce a continuous power output of 15 – 25 W, which provides sufficient energy to drive the high-voltage plasma generator. This generator operates at a high voltage of 10 – 15 kV with a low current of 1 – 10 mA, consisting of two metal electrodes, typically made of stainless steel, which are separated by a calculated air gap of only a few millimeters. When the voltage is applied, the air within this gap becomes ionized, forming the oxidative plasma required for sterilization. The physical design of the device is optimized for portability and field use, with dimensions of approximately 25 × 25 × 25 cm³, allowing it to be easily transported to various post-harvest locations. The internal plasma compartment is designed to accommodate approximately 1 kg of food products per treatment cycle. Based on power and efficiency simulations, one full battery charge is capable of supporting up to 25 sterilization cycles per day, with each cycle requiring an exposure time of 5 – 10 minutes depending on the specific characteristics and requirements of the food commodity being processed.

RESULTS AND DISCUSSION

Cold plasma technology has proven highly effective in inactivating pathogenic microorganisms on food surfaces without compromising sensory quality. Chemically, reactive species such as ions, ozone, and reactive oxygen species (ROS) generated under high-voltage conditions attack microbial cell walls through oxidation, leading to lipid peroxidation, direct structural damage, and inhibition of microbial metabolism [9, 10]. Non-thermal plasma treatments achieve rapid microbial reductions; for example, an 8-minute exposure for fresh fruits like apples results in a 3log reduction, extending shelf life by 3 – 7 days at room temperature with no significant changes in taste, texture, or color. Fresh milk treated for 10 minutes achieves > 3 log reduction and doubles shelf life while

maintaining stable color and aroma. Similarly, fresh meat shows 2 – 3 log reduction after 5 minutes of treatment, remaining viable for 5 – 7 days, and leafy greens like spinach exhibit > 99% microbial inactivation, extending shelf life by 7 – 10 days. Fermented products such as yogurt experience a 2log reduction after 7 minutes, increasing shelf life by 1.5 – 2 times with a slight increase in viscosity.

Energy efficiency is a key advantage of cold plasma systems. The PLASMAFOOD device consumes only 30 – 40 W per session, representing approximately 2% of the energy used by a standard household refrigerator [11]. This translates to potential energy savings of around 98%, making the technology an ideal green processing method that is both energy-efficient and chemical-free. Moreover, the

hybrid integration of renewable energy sources photovoltaic panels, thermoelectric generators, and piezoelectric units enables operation in remote areas lacking stable electricity, further enhancing sustainability. From an environmental perspective, cold plasma preservation has a much lower carbon footprint than conventional cooling systems. Total carbon emissions for plasma systems are approximately 0.12 kg CO₂ per kilogram of food, compared to over 3.5 kg CO₂ per kilogram for traditional refrigeration [12]. Since the technology does not require chemical refrigerants or produce hydrofluorocarbon (HFC) gases, it can reduce emissions by over 85%, supporting global efforts to mitigate the environmental impact of the cold chain [1].

Table 1. Log CFU/g reduction in microbial inactivation activity: A comparison of the effects of cold plasma technology on food quality and microbiology [11, 13].

Food type	Plasma exposure time (min)	Microbial reduction (log CFU/g)	Sensory changes (Taste, colour, texture)	Shelf life extension
Fresh fruit (Apple)	8	3 log	No significant changes	3 – 7 days at room temperature
Liquid milk	10	> 3 log	No colour changes, stable aroma	2x longer than control
Fresh meat	5	2 – 3 log	Texture maintained, slightly brighter colour	5 – 7 days at room temperature
Leafy vegetables (Spinach)	5	> 99% microbial reduction	No change in colour or texture	7 – 10 days at room temperature
Fermented product (Yogurt)	7	2 log	Texture maintained, slight increase in viscosity	1,5 – 2x longer shelf life

The socio-economic benefits of hybrid plasma technology are significant, particularly for rural farming communities. Extending shelf life by three to five times directly increases profit margins by 20–30% for small-scale producers [14]. The portable PLASMAFOOD device, costing less than 100 USD per unit using locally sourced components, exemplifies appropriate technology repairable, adaptable, and accessible. Farmers can maintain harvest

quality independently without costly cold chain infrastructure, reducing post-harvest food loss by up to 40%. This innovation supports Sustainable Development Goals (SDG) 7 for Clean and Affordable Energy and SDG 12 for Responsible Consumption and Production by promoting sustainable, zero-emission food preservation. In conclusion, cold plasma technology combines high microbiological effectiveness, extreme energy efficiency,

environmental of the sustainability, and socio-economic benefits, making it a promising non-thermal preservation method. Its hybrid renewable energy integration ensures applicability in remote and resource limited regions, providing a feasible and scalable solution to enhance global food security while minimizing environmental impact.

CONCLUSION

The development of a hybrid-powered portable cold plasma system represents an innovative approach demonstrating how science can overcome infrastructural limitations and provide practical solutions for food security. By utilizing the physical principles of ionization and controlled chemical oxidative reactions, this technology enables non-thermal preservation without degrading the nutritional value or sensory quality of food. Its low power requirement, energy efficiency, and ability to inactivate microorganisms by more than 99% make hybrid cold plasma systems highly suitable for practical application, particularly for farming communities in off-grid areas.

Beyond its function as a preservation tool, this system reflects the integration of physics, chemistry, and renewable energy technologies. By combining solar energy, thermal gradients, and environmental vibrations as energy sources, food preservation processes can be conducted independently of conventional electrical grids and chemical refrigeration systems. This innovation contributes directly to sustainable food systems by reducing post-harvest losses, lowering carbon emissions from cold chain logistics, and strengthening rural energy independence.

Future development of hybrid plasma systems can be directed toward community-scale implementation supported by Internet of Things (IoT) technologies for automated monitoring of temperature, processing time, and plasma voltage. Cross-sector collaboration among researchers, farmers, industry stakeholders, and policymakers will be essential to accelerate the integration of this technology

into sustainable agricultural ecosystems. Therefore, science-based solutions such as PLASMAFOOD should not remain confined to laboratory settings but must be translated into accessible and impactful technologies for communities with limited infrastructure.

REFERENCES

1. FAO. (2023). *The State of Food and Agriculture 2023 – Revealing the true cost of food to transform agri-food systems*. Rome. URL: <https://doi.org/10.4060/cc7724en>
2. Rajapakshe, P., Rathnasinghe, N., Guruge, K., Nilmini, R., Jayasinghe, R., Karunaratne, V., Wijesena, R., & Priyadarshana, G. (2025). Strategies to minimize post-harvest waste of fruits and vegetables: Current solutions and future perspectives. *Journal of Future Foods*, **6**(3), 400–412.
3. Ma, S., Zhao, P., Song, T., Wang, Z., Xu, S., Guo, L., Wang, Z., Zhang, J., Zhang, H., Liu, D., Wang, X., & Rong, M. (2025). Inactivation of microbial and pest contamination in post-harvest wheat by plasma-activated gas. *Food Control*, **181**, 111796.
4. Song, C., Wang, J., Wu, L., Liu, J., Liu, G., Gong, D., Zhang, W., Wei, J., & Zhang, Z. (2025). Quality and physiological changes in fresh-cut mango fruit as affected by cold plasma-activated water. *Postharvest Biology and Technology*, **225**, 113524.
5. Hu, Z., Hu, Z., Zhang, H., Yu, Z., & Xie, Y. (2025). Antimicrobial effects of tannic acid combined with plasma-activated water and their application in strawberry preservation. *Foods*, **14**(13), 2216.
6. Khumsupan, D., Lin, S. P., Hsieh, C. W., Santoso, S. P., Chou, Y. J., Hsieh, K. C., Lin, H. W., Ting, Y., & Cheng, K. C. (2023). Current and potential applications of atmospheric cold plasma in the food industry. *Molecules*, **28**(13), 4903.

7. Domonkos, M., Tichá, P., Trejbal, J., & Demo, P. (2021). Applications of cold atmospheric pressure plasma technology in medicine, agriculture and food industry. *Applied Sciences*, **11**(11), 4809.
8. Zhang, T., Yang, T., Zhang, M., Bowen, C. R., & Yang, Y. (2020). Recent progress in hybridized nanogenerators for energy scavenging. *iScience*, **23**(11), 101689.
9. Chacha, J. S., Zhang, L., Ofoedu, C. E., Suleiman, R. A., Dotto, J. M., Roobab, U., Agunbiade, A. O., Duguma, H. T., Mkojera, B. T., Hossaini, S. M., Razaq, W. A., Shorstkii, I., Okpala, C. O. R., Korzeniowska, M., & Guiné, R. P. F. 2021. Revisiting non-thermal food processing and preservation methods—action mechanisms, pros and cons: A technological update (2016–2021). *Foods*, **10**(6), 1430.
10. Sharma, R., Nath, P. C., Rustagi, S., Sharma, M., Inbaraj, B. S., Dikkala, P. K., Nayak, P. K., & Sridhar, K. (2025). Cold plasma—A sustainable energy-efficient low-carbon food processing technology: Physicochemical characteristics, microbial inactivation, and industrial applications. *International Journal of Food Science*, **2025**(1), 4166141.
11. Abbas, H. M., Altamim, E. A., Salama, M., Fouad, M. T., & Zahran, H. A. (2024). Cold plasma technology: A sustainable approach to milk preservation by reducing pathogens and enhancing oxidative stability. *Sustainability*, **16**(20), 8754.
12. Keewan, M., Krishnamoorthy, R., Show, P. L., Tang, D. Y. Y., & Banat, F. (2025). Atmospheric-pressure cold plasma: A next-generation nonthermal technology for enhancing food safety, quality, and shelf life. *Food Frontiers*, **6**(6), 2766–2788.
13. López, M., Calvo, T., Prieto, M., Múgica-Vidal, R., Muro-Fraguas, I., Alba-Elías, F., & Alvarez-Ordóñez, A. (2019). A review on non-thermal atmospheric plasma for food preservation: Mode of action, determinants of effectiveness, and applications. *Front. Microbiol.*, **10**, 622.
14. Alaguthevar, R., Packialakshmi, J. S., Murugesan, B., Rhim, J. W., & Thiyaamoorthy, U. (2024). In-package cold plasma treatment to extend the shelf life of food. *Comprehensive Reviews in Food Science and Food Safety*, **23**(2).



This article uses a license
[Creative Commons Attribution
 4.0 International License](https://creativecommons.org/licenses/by-nc/4.0/)