Application of UV Irradiation in Food Preservation: Current Trends

[1]Satveer Jajra, [2]Dr. Ramchandra B
[1]M. Tech Research Scholar, Department of Dairy Technology, Dairy Science College, KVAFSU, Hebbal, Bengaluru - 560024, India.
[2]Professor and Head, Department of Dairy Microbiology, Dairy Science College, KVAFSU, Hebbal, Bengaluru - 560024, India.

Abstract—Food preservation is important for maintaining the safety and quality of food products. In recent years, ultraviolet (UV) irradiation has become popular as a nonthermal method for food preservation. Unlike heat treatments, UV technology can reduce harmful microorganisms without causing major damage to the nutritional and sensory quality of foods. Consumers today prefer foods that are fresh, natural, and free from chemical preservatives, which has increased the use of UV-C treatment in the food industry. UV-C radiation is effective against bacteria, molds, yeasts, and viruses because it damages their genetic material and prevents their multiplication. This technology is used in the preservation of fruits, vegetables, beverages, dairy products, meat products, and food-contact surfaces. New developments such as UV-LED systems and combined preservation techniques have improved the effectiveness of UV treatment. Even though UV irradiation has many advantages, some limitations like low penetration ability and uneven exposure still create challenges. This article provides information about the working principle, mechanism, applications, advantages, disadvantages, recent developments, and future possibilities of UV irradiation in food preservation.

Index Terms—UV irradiation, UV-C treatment, food preservation, nonthermal processing, microbial control, UV-LED, shelf life

I. INTRODUCTION

Food products can easily spoil because of microbial growth, enzymatic reactions, and environmental conditions. Preservation methods are therefore necessary to improve food safety and increase storage life. Conventional preservation methods such as heating and pasteurization are widely used in industries, but high temperatures may reduce nutritional value and change the natural characteristics of foods.

Nowadays, people are more interested in foods that are fresh, minimally processed, and free from chemical additives. Due to these changing preferences, food industries are focusing on nonthermal preservation methods. One such method is ultraviolet (UV) irradiation. UV treatment has gained attention because it can control microorganisms effectively while maintaining food quality. It is also considered environmentally friendly and relatively economical for industrial applications.

II. PRINCIPLE OF UV IRRADIATION

Ultraviolet radiation is a form of electromagnetic energy with wavelengths shorter than visible light. Depending on wavelength, UV radiation is classified into different categories.

UV Type	Wavelength Range	Characteristics
UV-A	315–400 nm	Causes fluorescence and oxidation
UV-B	280–315 nm	Responsible for sunburn and photochemical effects
UV-C	200–280 nm	Strong antimicrobial activity
Vacuum UV	100–200 nm	Highly energetic, limited industrial use

Among these types, UV-C is most commonly used in food preservation because of its germicidal property. UV-C light around 254 nm is especially effective in reducing microbial contamination. The radiation damages microbial DNA and RNA, which prevents the microorganisms from reproducing.

The effectiveness of UV treatment depends on several conditions are:

- Exposure duration
- Intensity of UV light
- Distance between food and UV source
- Surface condition of food
- Moisture level
- Turbidity in liquids
- Type of microorganism's present

III. MECHANISM OF MICROBIAL INACTIVATION

3.1 Damage to Genetic Material

The main effect of UV-C light on microorganisms is damage to their genetic material. When microorganisms are exposed to UV radiation, changes occur in their DNA structure. These changes prevent the cells from multiplying normally and affect important activities such as growth and protein synthesis. As a result, the microorganisms gradually become inactive and die.

3.2 Production of Reactive Molecules
UV treatment may also lead to the formation of reactive oxygen species (ROS) inside microbial cells. These reactive molecules can attack important cellular components like proteins, enzymes, and membrane structures. This weakens the microorganism and reduces its survival ability.

3.3 Disturbance of Cell Functions
Longer exposure to UV light can disturb the normal functioning of microbial cells. It may affect membrane stability and interrupt metabolic reactions required for survival. Due to these effects, the cells lose their activity and eventually die.

3.4 Factors Influencing UV Sensitivity
Not all microorganisms respond to UV treatment in the same way. Their sensitivity depends on factors such as cell wall thickness, pigmentation, moisture conditions, and the ability to repair damaged DNA. In general, Gram-negative bacteria are more easily affected by UV-C light compared to Gram-positive bacteria because their cell walls are thinner and less protective.

IV. TYPES OF UV SYSTEMS USED IN THE FOOD INDUSTRY

Various UV systems are used in the food industry for preserving food products and maintaining hygiene during processing. These systems differ in their working method, intensity of radiation, and industrial applications.

Low-Pressure Mercury Lamps: Low-pressure mercury lamps are among the most commonly used UV systems in food processing plants. These lamps mainly produce UV light at a wavelength of 253.7 nm, which is highly effective against microorganisms. They are widely used for disinfecting water, sanitizing food-contact surfaces, and treating air in processing areas.

Medium-Pressure Mercury Lamps: Medium-pressure mercury lamps generate UV radiation over a broader wavelength range. Compared to low-pressure lamps, they provide higher intensity radiation and shorter treatment times. These systems are useful when rapid microbial reduction is required in industrial operations.

Pulsed UV Light Systems: Pulsed UV systems work by releasing powerful flashes of UV light within a very short time. The intense pulses help destroy microorganisms quickly and are often used for surface sterilization of packaging materials, fruits, vegetables, and ready-to-eat foods.

UV-LED Systems: UV-LED technology is a newer development in food preservation. These systems consume less electricity, produce less heat, and have a longer working life compared to traditional mercury lamps. Another advantage is that they do not contain mercury, making them safer for the environment. Due to these benefits, UV-LED systems are becoming increasingly popular in modern food industries.

V. APPLICATIONS OF UV IRRADIATION IN FOOD PRESERVATION

5.1 Fruits and Vegetables

Fresh fruits and vegetables spoil quickly because they contain high amounts of moisture and nutrients that support microbial growth. UV-C treatment is widely used to reduce microorganisms present on the surface of fresh produce and to slow down spoilage during storage.

Fruits: UV treatment is commonly applied to fruits such as strawberries, apples, grapes, tomatoes, and berries. It helps lower the number of harmful microorganisms and can also reduce fungal growth that causes decay. In some fruits, UV exposure may help maintain freshness, texture, and appearance for a longer time.

Vegetables: Vegetables like lettuce, spinach, carrots, broccoli, and cabbage are also treated with UV light to improve their storage quality. UV treatment helps reduce surface contamination and delays spoilage, which can increase shelf life during refrigerated storage.

Combination Preservation Methods: Food industries often combine UV treatment with other preservation techniques for better results. Methods such as cold storage, ozone treatment, edible coatings, and modified atmosphere packaging are frequently used together with UV irradiation to improve microbial control and maintain product quality.

5.2 Liquid Foods and Beverages

UV irradiation is used in liquid food products such as fruit juices, vegetable juices, flavored drinks, milk alternatives, and soft beverages. Since UV treatment does not involve high temperatures, it helps preserve natural flavor and nutrients more effectively than some thermal methods. It is mainly used to improve microbial safety and reduce spoilage microorganisms. However, UV treatment works better in clear liquids because cloudy or thick liquids reduce light penetration.

5.3 Dairy Products

In dairy processing industries, UV treatment is used for products like milk, whey, and cheese surfaces. The main purpose is to reduce microbial contamination while protecting heat-sensitive nutrients. UV systems are also used for sanitizing dairy equipment and processing environments to maintain hygiene.

5.4 Meat and Seafood

UV irradiation is applied to poultry products, fish, shrimp, and ready-to-eat meat items to reduce spoilage microorganisms and harmful bacteria. Surface treatment with UV light can help improve shelf life and reduce contamination during storage and handling.

5.5 Water and Air Treatment

UV systems are commonly installed in food processing plants for water purification and air sterilization. Treated water is used for washing raw materials and cleaning equipment. UV air treatment helps reduce airborne microorganisms in processing and packaging areas, improving overall hygiene and food safety.

VI. ADVANTAGES OF UV IRRADIATION

UV irradiation offers several benefits in food preservation and is considered an effective alternative to some traditional preservation methods. Since it is a nonthermal process, it helps maintain the quality of food while improving microbial safety.

- Minimal Heat Damage: UV treatment does not require high temperatures, so the natural taste, texture, and color of foods are better preserved.
- Chemical-Free Preservation: The process does not involve the use of chemical preservatives, which helps avoid chemical residues on food products.
- Better Nutrient Retention: Important nutrients such as vitamins, antioxidants, and other bioactive compounds are retained more effectively compared to certain heat treatments.
- Lower Energy Requirement: UV systems generally consume less energy, making them more economical for food industries.
- Environmentally Friendly Method: UV technology produces very little environmental pollution and is considered safer for sustainable food processing.
- Fast Processing: Microbial reduction can be achieved within a short period, which improves processing efficiency.
- Reduced Operating Cost: Maintenance and operational costs of UV systems are often lower than some conventional preservation technologies.
- Suitable for Fresh and Minimally Processed Foods: UV irradiation is especially useful for foods that require minimal processing while maintaining freshness and quality.

VII. DISADVANTAGES OF UV IRRADIATION

Also, UV irradiation is useful in food preservation, it also has certain limitations that reduce its effectiveness in some applications.

- Limited Penetration Ability: UV light cannot penetrate deeply into solid or opaque foods. Because of this, the treatment mainly affects the surface area and may not destroy microorganisms present inside the product.
- Uneven Exposure: Foods with rough or irregular surfaces may not receive uniform UV exposure. Some areas can remain untreated due to shadow effects, which lowers microbial reduction efficiency.
- Less Effective in Cloudy Liquids: In turbid or thick liquids, suspended particles can block UV light and reduce its ability to inactivate microorganisms effectively.
- Possible Changes in Food Quality: Excessive UV treatment may sometimes affect food color, texture, flavor, or overall sensory quality, especially in sensitive products.

- Microbial Repair Mechanisms: Certain microorganisms have the ability to repair UV-induced DNA damage under favorable conditions, which may reduce the overall effectiveness of treatment.
- Worker Safety Concerns: Direct exposure to UV radiation can be harmful to human skin and eyes. Therefore, proper safety measures and protective equipment are necessary during operation.
- Regulatory Differences: Rules and guidelines related to UV treatment in foods are not the same in all countries, which can create challenges for food industries and international trade.

VIII. RECENT DEVELOPMENTS IN UV FOOD PRESERVATION

Continuous research and technological improvements have increased the importance of UV irradiation in modern food preservation. New systems and combined preservation methods are helping improve both food safety and product quality.

UV-LED Technology: UV-LED technology is one of the latest developments in UV food processing. These systems are gaining popularity because they consume less electricity, produce less heat, and have a longer working life than traditional mercury lamps. Another important advantage is that UV-LED systems do not contain mercury, making them safer for the environment. Their compact size and easy operation also make them suitable for modern food industries.

Combination Preservation Techniques: Researchers are now combining UV treatment with other preservation methods to increase microbial reduction and improve storage quality. This approach is often called combined or hurdle preservation technology. And using these techniques together can improve preservation efficiency while reducing negative effects on food quality.

Some commonly combined methods are:
- Ultrasound
- Ozone treatment
- Cold plasma
- Essential oils
- High-pressure processing

Smart UV Systems: Modern UV processing equipment is becoming more advanced with the use of sensors and automated monitoring systems. These smart systems help control UV intensity, treatment time, and exposure conditions more accurately. As a result, treatment becomes more uniform and efficient.

Packaging Applications: UV irradiation is also being used for sterilization of food packaging materials before filling and sealing. It helps reduce microbial contamination on packaging surfaces and improves product safety. UV treatment is increasingly applied in biodegradable and eco-friendly packaging systems as well.

IX. FUTURE PROSPECTS

UV irradiation technology is expected to play a bigger role in future food preservation because of increasing demand for safe, fresh, and minimally processed foods. Researchers are continuously working on improving the efficiency and industrial applications of UV systems.
Some important future areas of development include:

- Improvement of UV-LED Technology: Scientists are focusing on developing more efficient UV-LED systems with better energy performance, longer lifespan, and stronger antimicrobial activity.
- Advanced Reactor Design for Liquid Foods: Better reactor systems are being designed to improve UV light distribution in liquid foods such as juices and beverages. These improvements may help overcome problems related to poor penetration in cloudy liquids.
- Treatment of Opaque and Solid Foods: Future research aims to increase the effectiveness of UV treatment in opaque, thick, and solid food products where light penetration is limited.
- AI-Based Monitoring Systems: Artificial intelligence and sensor technologies may be used to automatically monitor UV intensity, exposure time, and treatment conditions for more accurate processing.
- Development of Combination Preservation Methods: Researchers are studying the combined use of UV irradiation with other preservation techniques to improve microbial control and maintain food quality.
- Integration with Smart Packaging: UV technology may also become part of advanced smart packaging systems that help improve food safety, hygiene, and storage stability.

X. CONCLUSION

UV irradiation has become an important nonthermal method for preserving food and improving food safety. UV-C treatment is effective in reducing harmful microorganisms and helps extend the storage life of different food products without causing major changes in their nutritional and sensory properties. Because the process does not require chemical preservatives or high temperatures, it is considered suitable for modern food processing industries. The technology provides several benefits such as low energy usage, faster processing, and better retention of food quality. However, some limitations still exist, including low penetration ability in solid foods and uneven exposure on irregular surfaces. These challenges need further improvement for wider industrial application. Recent developments such as UV-LED systems, smart monitoring equipment, and combined preservation techniques have increased the efficiency and practical use of UV treatment. With increasing consumer preference for fresh, safe, and minimally processed foods, UV irradiation is expected to become more important in future food preservation and processing systems.

REFERENCES

[1] Koutchma, T., "UV light technologies for food and beverage preservation," *Food Engineering Reviews*, vol. 12, no. 4, pp. 456–472, 2020.

[2] Gupta, R., and Sharma, R., "Emerging applications of UV-LED technology in food preservation," *Journal of Food Processing and Preservation*, vol. 45, no. 5, Art. no. e15422, 2021.

[3] Gómez-López, V. M., and Rajkovic, A., "UV technologies for food safety and quality preservation: Recent advances and future trends," *Current Opinion in Food Science*, vol. 42, pp. 1–8, 2021.

[4] Manzocco, L., Nicoli, M. C., and Agriopoulou, S., "Nonthermal technologies in food processing: UV irradiation applications and challenges," *Foods*, vol. 10, no. 8, Art. no. 1826, 2021.

[5] Patras, A., Bhullar, M. S., and Pendyala, B., "Applications of ultraviolet light in minimally processed foods," *Foods*, vol. 11, no. 3, Art. no. 420, 2022.

[6] Koutchma, T., "Advances in UV-C LED systems for liquid food processing," *Innovative Food Science & Emerging Technologies*, vol. 76, Art. no. 102914, 2022.

[7] Ferreira, M. D., and Silva, F. V. M., "UV-C processing of fruit juices: Current status and future prospects," *Beverages*, vol. 8, no. 2, Art. no. 31, 2022.

[8] Singh, A., and Sharma, P., "Combination preservation technologies involving UV treatment in food industries," *Journal of Food Science and Technology*, vol. 59, no. 11, pp. 4205–4218, 2022.

[9] Chen, H., and Hoover, D. G., "UV irradiation and hurdle technology for microbial safety in foods," *Food Control*, vol. 145, Art. no. 109420, 2023.

[10] Zhang, Y., Wang, J., and Liu, X., "Smart UV processing systems in modern food industries," *Trends in Food Science & Technology*, vol. 134, pp. 150–162, 2023.

[11] Bhardwaj, S., and Kaushik, P., "Role of UV-LED technology in sustainable food preservation systems," *Sustainability*, vol. 15, no. 9, Art. no. 7024, 2023.

[12] Food and Agriculture Organization of the United Nations (FAO), *Nonthermal Food Preservation Technologies and Food Safety*. Rome, Italy: FAO, 2023.

[13] Kumar, N., and Mehta, R., "Recent developments in UV-C irradiation for food preservation: A review," *Food Reviews International*, vol. 40, no. 2, pp. 215–238, 2024.

[14] Li, Q., Zhao, H., and Chen, Y., "Advances in UV treatment of dairy and beverage products," *Journal of Dairy Science*, vol. 107, no. 1, pp. 55–69, 2024.

[15] World Health Organization (WHO), *Food Safety and Emerging Nonthermal Technologies*. Geneva, Switzerland: World Health Organization, 2024.