

New Non-Thermal Approach for Milk Sterilization: Ultraviolet Sterilization (UV-C): Principles, Engineering, Microbial Efficacy, Nutritional and Sensory Attributes and Future Prospects for Industrial Adoption

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Abstract:

Fresh bovine milk is highly assailable to microbial contamination, conventionally controlled by pasteurization and ultra-high temperature (UHT) processing. Despite being effective thermal methods it often compromise with nutritional and sensory quality of fresh milk and dairy products. Ultraviolet (UV-C) irradiation can be a promising non-thermal alternative, capable of inactivating the spoilage and pathogenic microbial species *via* photochemical disruption of DNA and proteins.

Keywords: UV-C irradiation of dairy, pasteurization, ultra-high temperature (UHT), shelf life.

1. Introduction.

Milk is the essential and foundation in human nutrition containing proteins, fats, polysaccharides, vitamins and minerals. Microbial spoilage and pathogenic contamination caused by *E. coli*, *Listeria monocytogenes*, *Staphylococcus aureus* are linked to food safety risks. Heat treatment ensures milk safety but reduces the vitamin content, proteins denaturation and affects the flavor. UV-C irradiation between 200–280 nm is non-thermal, eco-friendly method, aligns well with consumer prospect for minimally processed foods. UV-C ionized photons generate thymine dimers in microbial DNA, preventing replication of targeted microbes. UV-C irradiation have been found effective against coliforms, gram-negative bacteria and filamentous and non-filamentous fungi. UV-C wave penetrates poorly in opaque liquids, whereas the turbidity restricts depth $<0.1 \text{ mm}^{1-2}$.

The use of thin-film reactors for spreading milk into micro-layers for uniform exposure and spiral-flow systems for the enhancement of residence time and maximize UV-C contact. Ultrasonic pre-treatment also reduces particle size, improving transparency. Modular UV-C chambers enables the continuous flow sterilization for industrial scale project. Nutritional integrity in UV-C causes minimal loss of riboflavin and vitamin A compared to pasteurization. High risk of lipid peroxidation leading to off-flavors, gap in its dissipation requires the optimization of process parameter. UV-C treatment significantly reduces microbial load, while extending the storage stability of the dairy based products³⁻⁷.

2. Materials and Methods.

To identify peer-reviewed studies for the evaluating UV-C irradiation effects on the milk quality, microbial safety, detoxification, and shelf life improvement, we searched multiple academic databases like Google Scholar, Scopus, PubMed and Web of Science, postscript by institutional access to ScienceDirect, Springer and Wiley Online Library. Keywords used were: “UV-C irradiation of dairy, pasteurization, ultra-high temperature (UHT), shelf life. Selected studies investigated UV-C irradiation (200–280 nm) applied to milk or milk products. The studies were excluded if related to non-dairy matrices (e.g., Beverages, water). Also the reports devoid of quantitative data on microbial reduction, detoxification or milk quality parameters were removed for the main study. The experimental conditions for study were UV-C wavelength, fluency/dose, reactor design, flow rate, treatment time, and sample characteristics (fat content, turbidity, depth), while the microbial data indicating the log reductions of *coliforms*, lactic acid bacteria, *E.*

coli O157:H7, *Staphylococcus spp.*, and *Bacillus cereus* spores. The Chemical outcomes were reduction of aflatoxin M1 and lipid peroxidation (TBARS assay) with quality outcomes as changes in pH, color, aroma-active compounds, and bioactive proteins retention, also affecting shelf life outcomes due to microbial regrowth, toxin persistence, and storage stability under refrigeration.

3. Energetic and principles UV-C (Ultraviolet irradiation)

UV-C irradiation work via photon and matter interactions, the photons or packets of lights of specific wavelength (254 nm) carry the energy:

$$E = \frac{hc}{\lambda}$$

Where,

h = Planck constant (6.626×10^{-34} J·s)

c = light intensity (3×10^8 m/s)

$\lambda = 254 \times 10^{-9}$ m, giving the yields $E = 7.83 \times 10^{-19}$ J/photon, which is equals to **4.89 eV**, sufficient to disintegrate the microbial DNA bonds (thymine dimmers) and interferes with enzymatic activity in cell metabolism. Milk's opacity cause photon scattering due to fat globules, casein micelles and other minor constituents macro-molecules present in the milk, decreasing the UV-C wave penetration depth, the reactor design (thin-film/turbulent flow) combat this by maintaining laminar layers upto <1 mm thick. Only ~ 5–10 % of UV-C energy transform into heat, keeping the temperature rise below 2 °C. The effective germicidal efficiency show dependency on photon flux density (mW/cm²) and exposure time of the particular treatment selected. The fluency for microbial inactivation is **10–40 mJ/cm²**, consuming **0.1–0.3 kW/L**, lower than pasteurization (~1.5 kW/L)^{1,2}.

UV-C treatment chamber use less electrical energy than pasteurization, also reduce carbon footprint index. The reactor geometry, UV-C treatment effectiveness, and refractive index within chamber gives energy utilization and makes it more efficient. The high-output mercury or LED lamps with > 30 % conversion efficiency also increase germicidal power per watt. Combining the UV-C with several hurdles like microfiltration or microwave heating improves microbial reduction without increasing total energy demand. UV-C treatment's energetics are governed by **high photon energy, low thermal conversion, and efficient reactor design**, making it a **low-energy, high-impact technology** for milk preservation^{7,3}.

4. Comparative Perspective

UV-C irradiation at 254 nm is a powerful non-thermal technology for improving milk safety, quality, and shelf life. Multiple investigations shows that UVC effectively inactivates diverse microbial populations, including coliforms, *E. coli* O157:H7, *Staphylococcus spp.*, and even germinated *Bacillus cereus* spores, with synergistic effects when combined with microwave heating or microfiltration. Importantly, UVC not only reduces microbial loads but also minimizes the risk of pathogen reactivation during storage, thereby extending shelf stability under refrigeration. Beyond microbial safety, UVC has shown promise in reducing chemical hazards such as aflatoxin M1 by up to 50%, further enhancing milk's safety profile. Quality assessments consistently reveal that UVC-treated milk retains its sensory attributes, nutritional proteins, and oxidative stability better than conventional pasteurization, with only minor changes in pH or color. When optimized through reactor design, dosage, and process parameters, UVC irradiation emerges as an environmentally friendly, cost-effective, and sustainable preservation strategy that ensures microbiological safety, reduces toxins, and maintains the physicochemical and sensory qualities of milk, ultimately extending its shelf life without compromising consumer acceptability¹⁻⁷.

Table 1. Comparative analysis of the literature cited in brief.

Focus	Target species	Treatment	Key Findings	Effect on Quality	Shelf Life Impact
Raw bovine milk (thin-film reactor, 144 W, 3 L/min).	Coliforms, staphylococci, lactic acid bacteria.	Continuous flow, 254 nm UV-C.	Microbial reduction, mostly in the medium/high bacterial loads.	Low rate of lipid peroxidation when compared to pasteurized milk.	Reduction in oxidative radicals upto 72 h.
UVC vs. Ultrasound.	Coliforms, <i>E. coli</i> , <i>Staphylococcus spp.</i>	254 nm UV-C, in batch process.	Coliforms, <i>E. coli</i> , <i>Staphylococcus spp.</i> Destruction.	Minimal changes in aroma compounds: few new volatiles detected.	Comparably safe to thermal treatment, also the sensory quality retained.
<i>Bacillus cereus</i> spores activity in UV-C treatment chamber.	Germinated spores.	254 nm UV-C + microwave heating as hurdle approach.	Synergistic reduction in microbial population but resuscitation Reported.	low pH, otherwise stability in system (skim milk).	Good for skim milk or condensed milk.
<i>E. coli</i> O157:H7 reactivation.	Pathogenic gram negative bacteria.	222, 254, 282 nm UV-C, treatment.	254 nm UV-C most effective and lowest reactivation rate noted at 4 °C.	Minimal acidity/pH changes, acted as hurdle additionally.	Regrowth was lowest, extended shelf life stability.
Aflatoxin M1 reduction.	Chemical contaminant in milk and its products.	254 nm UV-C for 20 min.	50% reduction in toxins, influenced by depth, stirring, time	Color reduction, pH stable.	Improved chemical safety, supports longer storage
UV-C + Microfiltration	Vegetative bacteria and coliforms	Microfiltration + 254 nm, 39.3 mJ/cm ² for UV-C irradiation.	~5 log reduction to complete elimination were noted.	Bioactive proteins (lactoferrin, Ig, lactoperoxidase) retention.	Improve shelf life up to 40 days.

Brief outline of comparative analysis of UV-C treatment on milk and milk based products:

- I. Microbial inactivation: UVC reduced coliforms, *E. coli* O157:H7, *Staphylococcus spp.*, lactic acid bacteria, and even *Bacillus cereus* spores (especially when combined with microwave heating or microfiltration)⁵.
- II. Reactivation prevention: At 254 nm, UVC minimized the ability of pathogens like *E. coli* to recover, especially under refrigeration, which directly supports shelf life extension⁶.
- III. Chemical safety: UVC reduced aflatoxin M1 contamination in skim milk by ~50%, showing its dual role in microbial and toxin control⁴.
- IV. Quality preservation: Across all the studies, UV-C treated milk showed lower lipid peroxidation than pasteurized milk, retained bioactive proteins (lactoferrin, immunoglobulins, lactoperoxidase), and maintained sensory attributes with only minor changes in pH or color³.

V. Shelf life extension: Microfiltration + UV-C elevates skim milk's refrigerated life to 40 days, far beyond HTST pasteurization, while preventing microbial resuscitation⁷.

5. Challenges and future directions

Confined penetration of opaque matrices, oxidative changes in lipids and proteins portion of milk causing off flavour in milk and milk based products can be improve by use of regulatory hurdles for food-grade UV-C systems. The demand of attention towards consumer learning on non-thermal technologies leading future scope to hybrid preservation techniques (UV-C + HPP/PEF or cold plasma) and development of the innovative photoreactors with better penetration and effective results. Exploration of the natural photosensitizers (riboflavin, curcumin) to enhance microbial inactivation by its own activation, where the singlet reactive oxygen species invade free radicals and hinders oxidative stress in food samples like milk and milk based products. This cause its integration into sustainable dairy improvement and its better supply chains⁷.

While UV-C irradiation has shown strong tendency as non-thermal preservation technology in milk and milk based products preservation, but several challenges still persists before its widespread adoption into mainstream processing. One major limitation is the **optical opacity of milk**, where fat globules and proteins scatter and absorb UV-C light, reducing waves penetration depth and nonuniform in microbial inactivation. The reactor design, flow dynamics, and treatments must therefore be optimized for consistent exposure. Another challenge lies in improvement of UV-C systems for industrial adoption while maintaining energy efficiency and cost-effectiveness. Also the reports about concerns of secondary compound formation (such as minor volatile compounds (low molecular weight) changes and color shifts) needs further research to confirm its long-term sensory acceptability/consumer acceptability. The regulatory frameworks for UV-C use in dairy are still evolving and clear guidelines will be necessary to support commercialization^{2,3}.

Looking forward, the scope of UV-C technology is wide-screen. Combining hurdle approaches like microfiltration, microwave heating, or pulsed light aiding in acquiring microbial safety thereby extend shelf. In advance in a reactor engineering (thin-film systems and turbulent flow designs) exclusively, modify UV penetration in opaque liquids like milk by enhancing treatment range. Proteomics and metabolomics studies are in conformity with preservation of bioactive moieties or conjugate species like proteins and other nutritional components like fats, carbohydrates, strengthening consumer confidence over convenience food and feeds. Eventually, apart from pasteurization, UV-C aligns with sustainability goals in the dairy industry, and exists as environmentally friendly nature, low energy consumption. The continued optimization and regulatory support the UV-C irradiation treatment potential to become a mainstream technology for producing safe and high-quality milk with extended shelf life^{7,1,2}.

6. Conclusion

UVC irradiation guarantee microbiological safety and extends refrigerated storage conditions, significantly. Like 40 days, when microfiltration was applied to the UVC treatment, compared to conventional thermal pasteurization, UVC sourced advantages like energy efficiency, sustainability and protection of nutritional and sensory quality. Together, these findings establish UVC irradiation a promising, environmentally friendly alternative and complement to pasteurization, capable of meeting modern dairy industry demands for safe, high-quality milk with extended shelf stability.

7. References

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