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Reusable Smart Lids for Improving Food Safety at Household Level with Programmable UV-C Technology

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Abstract: The worldwide food industry faces the multiple challenges of providing food security while also reducing environmental and health consequences. This requires transitioning to chemical-free techniques of preserving food with a long shelf life that emphasize human health. Even though millions of people are experiencing hunger, the substantial amount of food that is being wasted is impeding the advancement towards UN Sustainable Development Goal 12, which aims to reduce food waste by 50% by the year 2030. On the other hand, conventional food preservation techniques still frequently depend on chemical additives, which might give rise to persistent health issues and potentially undermine nutritional quality. This emphasizes the necessity for inventive, non-chemical remedies that prioritize both prolonged storage duration and the safety of food. Consumer storage conditions, which are the ultimate phase of the food chain, still generate substantial waste because of the proliferation of mold and bacteria on fruits and vegetables, which presents health hazards. Enhancing storage conditions and extending shelf life is important. Low-frequency ultraviolet (UV-C) light technology provides a non-thermal and highly efficient method for fighting foodborne microorganisms such as mold. This method renders pathogens inactive while maintaining product quality, providing a cost-efficient and easily available alternative. This study proposes the development of a programmable "Smart-Lid" SLID storage system that utilizes upcycled home base glass jars with UV-C light-emitting lids to prevent mold growth on various open food items, including milk- and sugar-based food, sauces, and possibly dry meals. The research seeks to assess the efficacy and potential influence of the SLID solution with UV-C light's potential with programmable applications in this preserving environment at the home level.

Keywords: food security; food waste; sustainable food preservation; upcycling; UV-C technology; mold prevention

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1. Introduction

One of the most significant paradoxes in human history is the prioritization of the shelf life of food over human life in an ultimate consumer society. Additionally, it is also so tragic that packing materials have a much longer lifespan than the products. Packs are designed to safeguard, and for many consumer products, the packaging and preserving methods are as important as the product itself. Despite the use of various artificial conservation measures, a significant proportion of food items, specifically one-third, nonetheless end up being discarded before they can be consumed. According to the FAO's estimates, approximately one-third (1.3 billion tons) of all food produced globally is lost or wasted each year along the various stages of the food supply chain (FSC), from production, handling, and storage to processing, distribution, and consumption, which is generally known as "food lost waste" [1]. This remarkable statistic highlights the significant squandering of worldwide resources used in food production as well as the consequent rise in greenhouse gas emissions caused by lost or discarded food. Food losses, which occur at various stages of the food supply chain, are a complex global issue that requires careful consideration on a macro- and microscale [2]. Significant food loss occurs during the consumption phase in middle- and high-income countries, primarily due to inadequate storage conditions, excessive purchasing, and unregulated eating habits [1,3]. Consequently, people end up discarding food that is still suitable for consumption. In contrast, in low-income countries, food loss occurs primarily during the initial and intermediate stages of the food supply chain, with little waste at the consumer level [4]. Countries experience substantial losses at the beginning of their food supply chains. Harvest practices, adverse climate conditions for storage and cooling facilities, infrastructure limitations, and financial, managerial, and technical constraints in packaging and marketing systems are the primary factors contributing to food losses and waste in low-income nations [2]. Since many small-scale farmers in developing nations live on the verge of food insecurity, reducing food losses can quickly and significantly affect their means of subsistence. But one of the main points in food loss or the source of food waste is still present, and that can be addressed at the end of the supply chain [3,4]. Food loss and food waste (FL/FW) are global problems with significant economic, environmental, and social impacts. This total loss of food on every scale has several negative consequences:

- Economic losses: Food losses and waste amount to roughly USD 680 billion in industrialized countries and USD 310 billion in developing countries. FL/W represents a direct economic loss of approximately USD 990 billion per year [2]. Around 88 million tons of food are wasted annually in the EU, with associated costs estimated at EUR 143 billion [5].
- Environmental impacts: FL/FW also has a significant environmental impact. Food production that ultimately leads to loss or waste consumes significant amounts of water, energy, and land resources. It also contributes to greenhouse gas emissions by releasing methane, a potent greenhouse gas [2], as food decomposes in landfills. Food loss and waste account for about 4.4 gigatons of greenhouse gas (GHG) emissions per year. To put this in perspective, if food loss and waste were its own country, it would be the world's third largest GHG emitter, surpassed only by China and the United States [5,6].
- Social impacts: FL/FW is also a social injustice, as it occurs at a time when millions of people around the world are food insecure. It is estimated that the amount of food that is lost or wasted each year could be used to feed all the world's food-insecure people [7]. If we could save just one-fourth of the current global food loss or waste, it would suffice to feed 870 million hungry people [5].

Most of the food loss and waste (FL/FW) occurs at the later stages of the food chain, particularly at the retail and consumer levels. Statistics from the Food and Agriculture Organization (FAO) indicate that roughly 35% of global food production is lost or wasted at the consumer level alone [1,2]. This significant figure highlights the need for interventions that target consumer behavior and habits. There are critical factors contributing to whether consumer-level FL/FW best practices are followed:

- Retail and wholesale practices: Contracts between farmers and buyers can lead to produce waste. Rejection of food items based solely on appearance (shape, size, or cosmetic imperfections) can contribute to FL/FW [2].
- Consumer behavior: Poor planning, misunderstanding of "use by" dates, and casual attitudes towards food all contribute to consumer-level waste [3,4].
- Infrastructure limitations: Lack of proper storage facilities in homes can negatively impact food safety and freshness, leading to increased losses [3,6].
- Regional differences: Developed nations tend to have considerably higher per capita food waste compared to developing or underdeveloped countries. Consumers in Europe and North America discard an estimated 95–115 kg of food per person annually, while Sub-Saharan Africa and Southeast Asia see significantly lower waste at 6–11 kg per person per year [3,8].

1.1. The Aim of the Study

This study focuses on the FW outputs of home-based consumption and looks at a possible alternative solution for preserving and extending food life cycles. It investigates the potential consequences of utilizing a novel product/lid system known as the "Smart Lid" (SLID) and the potential consequences of employing low-frequency UV-C light as a micro-level preservation technique at the final stage of the food chain by upcycling home base waste glass jars (HBW). The “Smart Lid” (SLID) is a reusable lid/protection device that improves user awareness and optimizes the environment for storing healthy food by using UV-C lights. UV-C light technology remains a non-thermal method employed for decontaminating the surfaces of food and its environment. It is a healthy alternative approach that effectively inhibits the growth of bacteria and helps control losses during storage and transportation [7]. The SLID product provides cost-effective and customizable functionality for programmable UV-C food preservation microcontainers. These containers use low-frequency ultraviolet technology to prolong the freshness of consumer items in domestic settings.

This study aimed to repurpose and recycle discarded home glass packaging, with a specific emphasis on the jar groups with lids that are 85 mm in radius, with different volumes and heights. It also investigates the advantages and prospective applications of a programmable UV-C microproduct called the SLID (“Smart Lid”) to improve the longevity of household items on shelves. This innovative, small-scale solution aligns with sustainability principles and helps reduce food loss and waste across various food categories and scales, particularly at the end point of the supply chain in household settings. It also enhances safe food preservation by offering substitute products of different sizes, which can have major consequences. It is also crucial to evaluate the possible advantages that this healthy, smart solution can offer that also support the Sustainable Development Goals (SDGs), which call for reducing per capita global food waste at the retail and consumer levels and food losses along global production and supply chains by half by 2030. This supports the other SDGs, including the SD Target 2 goal of zero hunger by 2030 [1].

1.2. Problem of Food Loss/Waste (FL/FW)

From initial agricultural production to final household consumption, food waste occurs throughout the food supply chain (FSC). In medium- and high-income countries, food is largely wasted, meaning that it is thrown away even if it is still suitable for human consumption [2,9]. Significant food loss and waste do, however, also occur early in the food supply chain. In low-income countries, food is mainly lost during the early and middle stages of the food supply chain; much less food is wasted at the consumer level. Food loss (FL) and food waste (FW) differ in timing from production to consumption [3]. The Food and Agriculture Organization (FAO) of the United Nations defines food loss and waste as a decrease in the quantity or quality of food along the food supply chain. Within this framework, UN agencies distinguish between loss and waste at two different stages in the process [1,6]:

- Food loss (FL) occurs along the food supply chain from harvest/slaughter/catch up to but not including the sales level. Food loss (FL) happens early in the supply chain, before consumers purchase it. It can occur during cultivation, postharvest handling, processing, or transportation. According to the FAO, FL is defined as “a reduction in the quantity or quality of food resulting from decisions and actions by food suppliers within the chain, excluding retailers, food service providers, and consumers” [10].
- Food waste (FW) occurs at the retail, storage, and consumption levels. Store shelves, restaurant kitchens, or residences may abandon or render food unfit for ingestion. In contrast to FL, FW refers to a decline in food quantity or quality due to retailer, food service provider, and consumer decisions. According to the FAO, FW is “the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food service providers, and consumers”. In affluent countries, per capita food waste is considerable, making FW increasingly common [11].

While FL and FW definitions and metrics differ per organization, certain principles apply universally. On the other hand, food safety has increasingly integrated both themes since the outbreak [2,10]. Every stage of the food supply chain (FSC), from agricultural production to household consumption, results in food waste. Countries with medium and high incomes waste a significant amount of food, even if it is still suitable for human consumption [4]. Nevertheless, there is also a notable occurrence of food loss and waste at the beginning stages of the food supply chain. Low-income nations primarily experience food loss during the initial and intermediate phases of the food supply chain, resulting in significantly less food waste at the consumer level [1,2,11]. Food losses take place at the production, postharvest, and processing stages in the food supply chain. Food losses occurring at the end of the food chain (retail and final consumption) are rather called "food waste", which relates to retailers' and consumers' behavior [3]. This study only focuses on FW and food-preserving aims and attitudes in microscale applications for home-type customers. There are related issues that have affected the end user and customer food waste production, as follows:

1.2.1. Logistical Challenges

Challenges in the transportation and distribution of food, such as inadequate infrastructure, a lack of cold chain facilities, and transportation delays, can lead to food loss and waste, particularly for perishable items. A lack of cold chain infrastructure, particularly in developing regions, can lead to up to 50% spoilage of fruits and vegetables during transportation [6].

1.2.2. Market Dynamics

Economic factors such as market volatility, fluctuating prices, and consumer demand can contribute to food waste. Price advantages may occur due to overproduction or market fluctuations, resulting in excessive storage of food. The World Bank's research reveals that market fluctuations and unpredictable prices, particularly in countries with high inflation, lead to food waste by incentivizing the purchase of food products beyond necessity [8].

1.2.3. Sufficient Storage and Handling Issues at Home

Improper storage facilities and handling practices during transport and storage can lead to food spoilage and waste. Factors such as inadequate temperature control, humidity, and pest infestations can accelerate food deterioration. The FAO estimates that between 25 and 30% of postharvest losses in developing countries occur due to inadequate storage facilities and handling practices at the at the end of the supply chain [6].

1.2.4. Quality Standards and Aesthetic Preferences

Retailers' strict quality standards and consumers' preferences for visually appealing produce contribute to food waste. Retailers or consumers may reject fruits and vegetables that are imperfect or cosmetically blemished, even if they are perfectly edible. A study published in *Applied Economic Perspectives and Policy* [9] revealed that stringent cosmetic standards for fruits and vegetables can lead to up to 20% rejection rates by retailers, even if the produce is perfectly edible. At the retail level, large quantities of food are wasted due to quality standards that over-emphasize appearance [5].

1.2.5. Consumer Behavior

Consumer behavior has a significant impact on household food waste. Buying more food than needed, improper storage, and discarding edible food due to confusion over expiration dates or perceptions of freshness contribute to food waste [11]. Confusion over "use by" and "best before" labels significantly influence household food waste, resulting in premature disposal of edible food [12].

1.3. Food Base Contaminations and FW at Home Scale

Improper storage is a major culprit in food waste, turning perfectly good food into unnecessary discards. These are the "storage-related villains", and we will discuss the science underlying their destructive actions.

1.3.1. Insufficient Storage Conditions

This villain represents a multitude of offenses against proper food storage:

- Temperature Control: Improper temperature plays a significant role in spoilage rates. Studies have shown that storing fruits and vegetables at improper temperatures can significantly accelerate enzymatic activities that lead to softening, discoloration, and ultimately spoilage [13,14].
- Ventilation: Inadequate ventilation can trap moisture around produce, creating an ideal environment for mold and bacteria growth [3]. Research by the USDA indicates that proper ventilation in storage facilities can extend the shelf life of fruits and vegetables [15].
- Light Exposure: Food items have varying light sensitivity. Certain fruits and vegetables exposed to excessive light can experience accelerated ripening or chlorophyll degradation (loss of green color) [16].

1.3.2. Molds and Fungus

Despite various measures taken to prevent mold growth on food, molds are ubiquitous in nature and can contaminate products before, during, or after harvest, processing, storage, and sale (Table 1). Aspergillus, Cladosporium, Alternaria, Mucor, and Penicillium are the most-known molds that can easily grow and expand on food surfaces. Fruits are more susceptible to fungal spoilage than bacterial spoilage due to their characteristics such as high water activity, high sugar content, and low pH [17,18]. This significantly increases the risk of mold growth on fruits, posing a significant concern for food safety and waste. These unwelcome guests thrive in warm, moist environments. Improper storage practices, like leaving vegetables in sealed plastic bags that trap condensation, create a breeding ground for mold growth. Studies have shown that certain fungal species can produce mycotoxins, harmful substances that render food unsafe for consumption [19,20]. Molds degrade food and produce mycotoxins that harm human health, causing economic losses. As a result, foods that have mold can potentially pose a health risk [21]. By preventing food spoilage, preventive strategies and approaches effectively reduce economic losses and ensure food safety and preservation. While fungicides are increasingly employed to inhibit mold growth and the development of mycotoxins, the establishment of fungicide-resistant pathogenic strains remains an inevitable and favored means of attaining this objective. This method entails the excessive utilization of chemicals, but this method can also lead to the presence of unwanted residues on food surfaces and pose potential health hazards to humans [22]. When given the right conditions, the ubiquitous fungi Aspergillus, Cladosporium, Alternaria, Mucor, Rhizopus, Penicillium, and Geotrichum can thrive on a variety of food sources.

- Aspergillus is a genus of molds that includes a multitude of species, several of which can generate mycotoxins that can be detrimental to both people and animals. Aspergillus may thrive on various substrates, such as grains, nuts, dried fruits, and spices. It frequently causes food degradation and can lead to aflatoxin contamination, particularly in improperly stored grains and nuts. It can cause respiratory problems and allergies [20].
- Penicillium molds have a broad distribution in nature and are frequently present in soil, air, and decomposing plant matter. Fungi can thrive on a diverse range of food sources, such as grains, fruits, vegetables, and cheese. Food manufacturers use certain Penicillium species, like Penicillium roquefortine, in blue cheese. Other Penicillium species, however, can generate mycotoxins and contribute to food rotting under suitable conditions [22].

- Cladosporium is a prevalent genus of mold that can be found in both indoor and outdoor settings. It can thrive on a variety of organic materials, including food. Cladosporium species commonly inhabit fruits, vegetables, cheese, and bread. Despite the recognition that several species are allergenic, they generally do not produce significant quantities of mycotoxins [23].
- Mucor is a rapidly proliferating fungi commonly found in soil, plant remnants, and decomposing organic material. Fungi could thrive on a wide range of food sources, such as fruits, vegetables, bread, and dairy products. Mucor species are renowned for their swift proliferation and have the potential to induce food deterioration, especially in situations with high levels of moisture [23,24].
- Alternaria is one of the most common mold genera, and is found in soil, plants, and the air. It can thrive on a diverse array of substrates, encompassing fruits, vegetables, cereals, and dairy products. Researchers recognize Alternaria species for their capacity to produce allergens and mycotoxins, potentially leading to significant health consequences when consumed in excess [20].
- Rhizopus is a genus of common saprophytic fungi on plants and specialized parasites on animals. They are found in a wide variety of organic substances, including "mature fruits and vegetables", jellies, syrups, leather, bread, peanuts, and tobacco [22]. They are multicellular. Some Rhizopus species are opportunistic human pathogens that often cause a fatal disease called mucormycosis.

Table 1. Common home molds and affected foods [21,22].

Mold Name	Appearance	Affected Food Types	Potential Health Concerns
Aspergillus	Green or black spots with a powdery or fuzzy texture	Bread, cereals, nuts, dried fruits, damp walls/ceilings	Respiratory problems, allergies
Penicillium	Blue or green mold with a velvety or hairy texture	Bread, fruits, vegetables, meat, some cheeses (blue cheese)	Respiratory problems, allergies, some strains may produce toxins
Cladosporium	Black or dark brown mold with a furry or slimy texture	Fruits, vegetables, meat, damp walls/ceilings	Respiratory problems, allergies
Mucor	White or grey mold with a cottony or fluffy appearance	Soft fruits and vegetables, bread, cheese	Mucormycosis (serious fungal infection), especially for immunocompromised individuals
Rhizopus	Black or black-brown mold with a spiky or hairy texture	Bread, starchy foods, fruits, vegetables, meat	Black mold, potential health issues
Geotrichum (Dairy Only)	White or cream-colored mold with a slimy texture	Soft cheeses, yogurt	Spoilage, unpleasant flavor/odor

In general, these molds can thrive on various types of food, especially in environments with high levels of moisture, warmth, and inadequate storage methods. Adhering to appropriate methods of handling, storing, and maintaining cleanliness is crucial to preventing the formation of mold and the spoilage of food [20].

1.3.3. Bacterial Growth

Uncooked meats, dairy products, and leftovers become susceptible to rapid bacterial multiplication at room temperature (Table 2). Research highlights the importance of proper food storage temperatures to prevent foodborne illnesses caused by bacterial growth [20,23]. Here are the factors influencing bacterial growth in the food chain:

- Temperature: Bacteria thrive in warm conditions. The "danger zone" for bacterial growth is between 40 °F (4 °C) and 140 °F (60 °C).

- Moisture: Bacteria require moisture for growth. Foods with high moisture content are more susceptible to bacterial growth [18]. Food provides nutrients for bacteria to grow and reproduce.
- Time: The longer food is stored, the greater the opportunity for bacteria to grow.
- Initial Contamination: Food will spoil more quickly if it already contains bacteria when stored.
    a. Pathogenic bacteria: These pose a significant health risk because they can cause foodborne illness. Consuming food contaminated with these bacteria can lead to symptoms like diarrhea, vomiting, fever, and abdominal cramps. The severity of illness depends on the specific bacteria, the amount consumed, and the individual's health [20].
- Salmonella: This is commonly found in poultry, eggs, meat, and even fruits and vegetables [23,24].
- E. coli: Certain strains cause illness and are found in contaminated ground beef, unpasteurized milk, and leafy greens [23].
- Listeria monocytogenes: This grows at refrigeration temperatures and is risky for pregnant women and immunocompromised individuals. It is found in unpasteurized dairy products, deli meats, and pre-cooked hot dogs [24,25].
- Staphylococcus aureus (Staph): This produces toxins, causing food poisoning. It is found in contaminated meat, dairy products, and improperly handled prepared foods [23].
    b. Spoilage Bacteria: These bacteria do not necessarily cause illness, but they can ruin the quality and taste.
- Pseudomonas: This grows at refrigeration temperatures, causing slimy discoloration on meat and poultry [23,25].
- Lactobacillus: This is responsible for souring milk and other fermented products but can also spoil other foods [24].
- Bacillus: This is a spore-forming bacteria that survives harsh conditions and contributes to spoilage in canned goods or cooked rice [25].

Table 2. Common foodborne bacteria [24,25].

Bacteria Group	Examples	Causes	Affected Food Types	Typical Growth Conditions
Pathogenic Bacteria	Salmonella *Escherichia coli* (*E. coli*) *Listeria monocytogenes* *Staphylococcus aureus* (Staph)	Foodborne illness (diarrhea, vomiting, fever)	Poultry, eggs, meat, seafood, fruits, vegetables, unpasteurized milk	Warm temperatures (40 °F–140 °F)
Spoilage Bacteria	Pseudomonas Lactobacillus Bacillus	Food spoilage (unpleasant odors, textures, discoloration)	Meat, poultry, fish, dairy, products, fruits, vegetables, cooked rice	Varied, some grow at refrigeration temperatures, others at room temperature

1.3.4. Wrong Preserving Techniques

Mishandling preservation methods can backfire. For instance, storing certain fruits and vegetables together can accelerate the ripening process due to ethylene gas emissions. Improper canning or freezing techniques can compromise food safety by allowing for bacterial growth or spoilage [24,26].

1.3.5. Misunderstood Expired Dates

Confusion around "use by" and "best before" dates often lead to premature food waste. Understanding these labels goes a long way. "Use by" dates indicate a safety concern, while "best before" refers to quality. Proper storage can significantly extend the shelf life of food items even after the "best before" date [25].

By understanding these storage-related villains and employing proper food handling practices, we can significantly reduce food waste and contribute to a more sustainable food system.

1.4. Possible Household-Level Food Storage Practices

Storing food safely and according to proper conditions is an important issue to be considered in terms of food safety and has the potential to minimize FW production at home [1,4,8]. Healthy storage of food refers to the act of storing food in a specific and appropriate place for future use under the instructions for use over time [27]. Nowadays, while food safety and storage issues are becoming increasingly important due to inadequate food safety practices at the household level, it is seen in the regular research of global organizations such as the UN, FAO, and WHO that uncontrolled consumption habits and careless storage conditions lead to an increase in food waste on a global scale. Implementing the details of the methods commonly used for food safety, especially at the microscale (home and user), in a meticulous, orderly, and controlled manner has the potential to positively affect the hunger problem that threatens the whole world [4].

- Proper Storage: Utilize airtight containers, zipper-lock bags, or vacuum-sealed bags for storing leftovers, dry goods, and pantry essentials. This prevents moisture loss, contamination, and exposure to air, avoiding potential spoilage.
- Canning and Preserving: Consider canning, pickling, or preserving fruits and vegetables when they are in season. This allows you to enjoy them year-round and reduces food waste. Follow safe canning practices to prevent bacterial contamination [20].
- Store Dry Goods: Store dry foods including rice, pasta, flour, and cereals, in a cool, dry spot, away from direct sunlight and heat. Use sealed containers or resealable bags to protect them from pests and moisture [21].
- Temperature and Light Control: Pay attention to temperature- and light-sensitive foods and ingredients. To prevent flavor and texture changes, store potatoes, onions, and tomatoes in a cool, dark place outside the refrigerator [18].
- Cold Protection: Refrigeration is one of the most effective ways to store perishable foods such as dairy products, meats, and fresh produce. Keep your refrigerator temperature at or below 40 °F (4 °C) to slow down bacterial growth and extend the shelf life of foods.
- Freezing: Freezing is another excellent method for preserving food. Wrap foods tightly in freezer-safe packaging to prevent freezer burn, and label them with the date to ensure freshness. Freeze items like meat, poultry, fish, bread, fruits, and vegetables for longer-term storage [20].
- Anti-bacterial Surface: Chemical treatments on food packaging materials have antimicrobial properties that can help slow bacterial growth. Also, certain spices and herbs possess natural antimicrobial properties. While they may not eliminate bacteria entirely, they can contribute to improved food safety [24].
- Ultraviolet (UV) Light: UV light is a highly efficient and extensively employed industrial technology in the realm of food safety. It offers a range of solutions that can enhance food storage and safety. This is particularly crucial as the global demand for proper food preservation rises, driven by insufficient food safety measures. Nevertheless, the way in which low-frequency UV light in the food industry is used presents a significant barrier to UV technology's overall efficacy. This industrial technique can provide efficient protection not only during application (against actual and potential risks) but also after application (such as inadequate storage, transit, and sales locations). As a result of current practices, industrial UV light's application in the realm of food safety is not a long-lasting and efficient solution that covers every step from production to consumption. Conversely, multiple food safety studies have demonstrated that insufficient storage conditions in households and rising levels of individual consumption are causing an escalation in worldwide food waste at home. This study examines the feasibility of using intermittent and short-term low-frequency UV radiation to

provide sustainable food safety. The focus is on providing fundamental protection for food, particularly at the user level and in-home settings. Furthermore, researchers are also investigating the feasibility and convenience of using spot UV protection technology (LED technologies), which have previously demonstrated satisfactory energy efficiency in guaranteeing food safety in residential settings.

1.5. Food Preservation and Protection Using UV Technology

UV light is a powerful industrial technique that can significantly enhance the effectiveness of solution groups, leading to improved food storage and safety. Considering the growing demand for food storage worldwide because of insufficient food safety protocols, this is especially significant. However, low-frequency UV applications pose a significant obstacle to UV technology's widespread efficacy. The technique provides effective protection only while in use, but it is ineffective during transport, exposure, or storage if the application is not ongoing [27]. Studies, on the other hand, indicate that inadequate home storage conditions and rising levels of individual consumption contribute to the worsening of global food waste at the household level [6,9,23]. This study examines the potential application of intermittent and short-administered low-frequency UV radiation to offer fundamental safeguarding for delicate food items. Furthermore, it explores the practicality and accessibility of using point UV protection as a viable and efficient approach to ensuring food safety in domestic storage scenarios [28,29].

1.5.1. Optimization

Research indicates that ultraviolet (UV) radiation can eradicate microorganisms on food surfaces, prolong food shelf life, and ensure food safety by preserving freshness for extended periods of time. The industry widely acknowledges UV light systems as more cost-effective, practical, and health-friendly than other high-end protection choices. These techniques are widely used in the food industry to prevent rotting and extend the shelf life of perishable products, particularly dairy products. Furthermore, UV systems, with their exceptional energy efficiency and minimal maintenance needs, can serve as a focal point for cost-effective research in a range of sizes [21].

1.5.2. Usability and Comprehensiveness

Compact and cost-effective industrial and commercial premises are well-suited for food production and storage. UV sterilizers and lamps improve food safety at every stage of production, storage, and transportation. UV light technology, specifically LED technology, has the capability to enhance and be effortlessly incorporated into small-scale and specialized applications, such as residential surroundings [29]. Nevertheless, we have not yet achieved the successful integration of this technology with reusable product packaging. Utilizing specialized solutions involving long-term reusable containers can improve food safety by inhibiting bacterial proliferation and maintaining food quality and longevity in various storage locations, such as cupboards and freezers. The use of UV technology in residential storage is exceptional because of its long-term effectiveness and adaptability [20,28].

1.5.3. Ensuring Food Safety and Improving Efficiency

Ultraviolet (UV) light reduces the number of microorganisms on food surfaces, ensuring food safety. UV light is an excellent option for maintaining food safety at home since it can efficiently eliminate microorganisms, viruses, and fungi without the need for direct contact with the human eye. The capacity to permeate packaging materials and offer protection without affecting the quality or taste of food indicates the potential for additional progress [14,23,26].

1.5.4. Specialization and Programmable Solutions

Recent advancements in ultraviolet (UV) technology have enabled the development of customized UV systems specifically designed for food storage purposes. These devices have the capability to function at different levels of strength and frequency, depending on the specific type of food and the desired level of safety. These devices utilize accurate UV wavelengths to specifically target infections, resulting in focused antimicrobial actions. This customization showcases the capacity to create resilient, enduring storage solutions for a wide range of food items. UV protection is an optimal option for storing food at home because it is cost-effective, convenient, and provides advantages in terms of food safety [28].

Studies suggest that utilizing UV light systems can efficiently inhibit the growth of microorganisms in residential food storage areas, prolong the shelf life of highly perishable items, and decrease food spoilage. With the continuous improvement in the duration and effectiveness of food preservation systems, UV protection has become a critical global issue.

2. UV Light

Ultraviolet (UV) light means “beyond violet”, as violet is the highest frequency of light visible to the human eye. The electromagnetic spectrum of light that the human eye can detect is between 380 and 700 nanometers (nm) (Figure 1) [30]. UV lighting has a shorter wavelength and a higher frequency than visible violet light. German physicist Johann Ritter made the first discovery of UV light in 1801. The use of ultraviolet (UV) light for the treatment of skin conditions dates to the early 1900s. It is well known that sunlight can have therapeutic value, but it can also lead to deleterious effects such as burning and carcinogenesis. Extensive research has expanded our understanding of UV radiation and its effects on human systems and has led to the development of human-made UV sources that are more precise, safer, and more effective for treatment in a wide variety of areas [30]. UV light technology was first used for the disinfection of drinking water in France in 1906. Ultraviolet (UV) light technology has been emerging as a compelling alternative for industrial food preservation for around 60 years. Its ability to inactivate microorganisms and extend shelf life positions it as a valuable tool for both industrial-scale and household-level healthy food storage applications. Notably, current advancements in UV-A and UV-B both prevent carcinogenic side effects, but particularly UV-C light, which has the shortest wavelength and is suitable for various applications without harming human life. It has minimized waste production and has almost no environmental impact when used in industrial food processing [30–32]. Ultraviolet UV lighting can be categorized into four different areas:

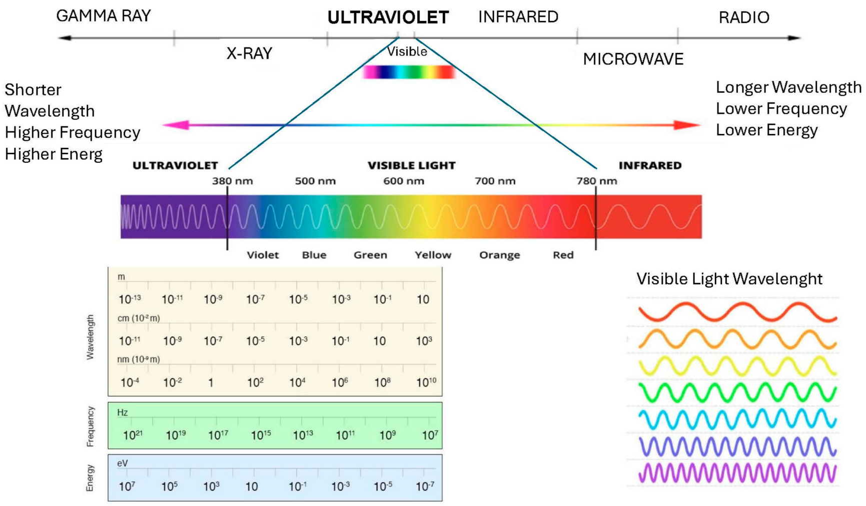

Figure 1. Conversion between wavelength, frequency and energy for the electromagnetic spectrum of light [30–36].

1. UV-A (315–400 nm): This is the longest wavelength of UV light and is emitted between 315 and 400 nm. UV-A is the least carcinogenic wavelength but still contributes to sunburns and skin cancer [32].
2. UV-B (280–315 nm): We refer to light that emits in the wavelength range of 280 to 320 nm as UV-B. It is more carcinogenic than UV-A; however, only about 5% of this light reaches the earth's surface.
3. UV-C (200–280 nm): This is the shortest wavelength of UV light, in the range of 100 to 280 nm. The sun emits UV-C light, the shortest wavelength of light, which the ozone layer completely absorbs, preventing it from ever reaching the Earth. Lamps designed to emit UV-C radiation in the range of 23.7 nm are used in many germicidal applications, such as UV air purification systems, UV water disinfection, and UV sterilization of critical surfaces [33,36].
4. Vacuum-UV (100–200 nm): Ultraviolet light with wavelengths in the 100–200 nm range (known as vacuum ultraviolet; VUV) has applications in nanofabrication, photochemistry, and spectroscopy [34].

Each category of UV lighting has very useful purposes for many industries and daily applications. UV-A and UV-B light are common in many medical phototherapy lamp spectrums, and UV-C lights in the range of mercury and low-frequency LED lamps demonstrate the strongest antimicrobial effectiveness, making them ideal for ensuring food safety.

2.1. Fundamental Approaches to UV-C Application: Pathogen Inactivation and Growth Inhibition

Ultraviolet-C (UV-C) light, with its short wavelength (200–280 nm) and germicidal properties, has emerged as a promising technology for food preservation. Its ability to inactivate microorganisms makes it a valuable tool for enhancing food safety and extending shelf life [30]. We can broadly categorize the application of UV-C light in food preservation into two primary approaches.

2.1.1. Pathogen Inactivation

The primary focus of UV-C light application in food preservation is to eliminate or significantly reduce the presence of pathogenic microorganisms, such as bacteria, viruses, and parasites, that can cause foodborne illnesses. This approach aims to prevent these pathogens from contaminating food products in the first place, ensuring their absence and minimizing the risk of foodborne diseases.

a. Key objectives of inhibition:
    1. Eliminate pathogens: Inactivate a significant proportion of, or all, the present pathogenic microorganisms. Prevent foodborne illnesses; reduce the risk of consumers contracting illnesses caused by contaminated food products.
    2. Enhance food safety: Contribute to a safer and healthier food supply.
    3. Surface decontamination: Treat food product surfaces, packaging materials, and equipment to eliminate pathogens before or after product contact.
    4. Liquid food treatment: Apply UV-C light to liquid food products, such as juices, milk, and beverages, to inactivate pathogens while preserving nutrients and sensory qualities.

2.1.2. Microbial Growth Inhibition

In contrast to pathogen inactivation, which targets the elimination of existing microorganisms, microbial growth inhibition, on the other hand, focuses on preventing or retarding the growth and reproduction of microorganisms that may be present in food products. This approach aims to extend the shelf life of food by controlling microbial populations and delaying spoilage [25].

a. Key objectives of inhibition:

    1. Slow microbial growth: Reduce the rate at which microorganisms grow and multiply in food products.
    2. Extend shelf life: Delay the onset of spoilage and maintain food quality for a longer period.
    3. Minimize food waste: Reduce losses due to microbial spoilage and extend the availability of food products.
    4. Inhibit microbial growth and extend shelf life: To do this, apply UV-C light to fresh fruits and vegetables after harvest.

b. In-package treatment: Integrate UV-C light sources into packaging materials to continuously suppress microbial growth within the package.
c. Modified atmosphere packaging: Combine UV-C treatment with modified atmosphere packaging to create an environment less conducive to microbial growth.

2.1.3. Academic Perspectives and Discussions

The application of UV-C light in food preservation has sparked extensive research and discussions among scientists and food industry professionals [26,28,30]. Key areas of focus include the following:

- Effectiveness: Evaluating the efficacy of UV-C light treatment against various pathogens and microorganisms under different conditions.
- Food quality: Assessing the impact of UV-C light exposure on food quality attributes such as nutrient content, sensory properties, and texture.
- Safety considerations: These include ensuring the safe and appropriate use of UV-C light technology and addressing potential hazards such as ozone generation and photochemical reactions.
- Regulatory frameworks: Establishing clear guidelines and regulations for the application of UV-C light in food processing and preservation.

2.2. UV-C Light Application and Potential Effects in Food Preservation

UV-C light is a disinfection method used to extend the shelf life of foods and control microbiological contamination. The effectiveness of this method depends on various factors, including wavelength, dose, and application time [37]. The two fundamental effects of UV-C light on foods are described below.

2.2.1. Microbial Inactivation

UV-C light has two primary effects on foods: microbial inactivation and chemical changes. Both factors can have a significant impact on a food's shelf life and nutritional value. Selecting the appropriate wavelength, dose, and application time is crucial for the effectiveness and safety of UV-C light treatment in food processing. UV-C light has the ability to inactivate microorganisms by damaging their DNA. This effect encompasses bacteria, viruses, fungi, and molds. The microbial inactivation efficacy of UV-C light depends on the type of microorganism, the structure of the cell wall, and the exposure time to UV-C light [38]. Researchers have investigated the effectiveness of UV-C light in inactivating pathogens such as Escherichia coli and Salmonella Typhimurium on fruits and vegetables. Their findings demonstrated that UV-C light significantly reduced these pathogens and extended the food's shelf life [39]. Researchers have also examined the efficacy of UV-C light in inactivating pathogens like Staphylococcus aureus and Listeria monocytogenes in dairy products. The results showed that UV-C light significantly reduced these pathogens and extended the food's shelf life. Microbial genetic material (DNA or RNA) is particularly susceptible to UV photons within the UV-C range, with a peak absorption wavelength of around 260–265 nm [34]. For the past two decades, UV-C radiation at 253.7 nm has been the preferred method for pasteurization and shelf-life extension, particularly for beverages [35].

The primary mechanism of action involves UV-C irradiation causing damage to microbial nucleic acids (Figure 2) [33]. This damage, often manifested as the formation of dimers between pyrimidine bases within DNA strands, disrupts microbial replication and ultimately leads to cell death [31].

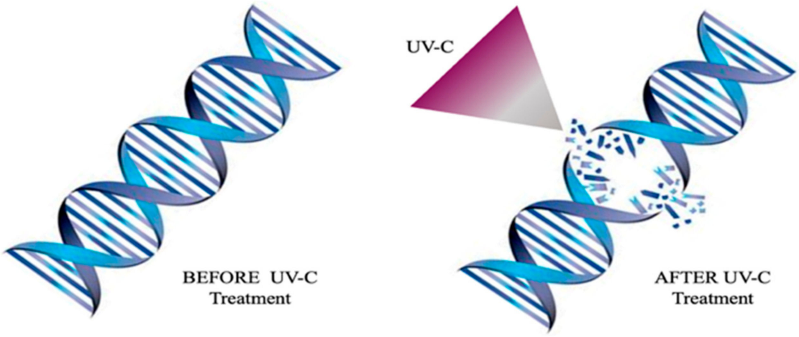

Figure 2. Ultraviolet-C (UV-C) (germicidal) radiation disrupts the DNA and RNA molecules of a pathogen, preventing its replication and rendering it incapable of causing infection, thereby eliminating its threat. Ultraviolet-C (UV-C) radiation renders viruses, bacteria, and fungi nonfunctional.

2.2.2. Chemical Effects/Changes

UV-C light has the ability to cause chemical changes in food components. This effect can lead to the loss of vitamins, enzymes, and other nutrients. The extent of chemical changes caused by UV-C light depends on the type of food, the wavelength of UV-C light, and the dose [40]. Researchers have studied the effect of UV-C light on the vitamin C content of orange juice. Their results indicated that UV-C light caused a significant decrease in vitamin C content [40]. Investigated the effect of UV-C light on the amino acid content of milk has also been investigated. The findings revealed that UV-C light caused a significant decrease in the content of certain amino acids. On the other hand, unlike traditional methods reliant on chemical preservatives, UV treatment presents a sustainable and human-friendly approach to food safety. This growing interest in UV technology also stems from the limitations of traditional thermal food processing methods. Thermal processing, while effective at eliminating pathogens, can compromise the nutritional value and sensory characteristics of food [30]. Furthermore, research suggests that UV-C light not only inactivates microbes but also possesses the potential to enhance the nutritional qualities of fruits and vegetables [33]. Regular UV-C application can reduce microbial proliferation, eliminate harmful organisms, and even suppress their genetic mutation, offering additional benefits beyond simple preservation [31,32]. Researchers are actively exploring low-temperature alternatives like UV irradiation that prioritize the retention of high quality and cause minimal nutritional loss, ultimately delivering safe and delicious food products [34]. Among these non-thermal processing methods, UV light holds significant promise for pathogen reduction while minimizing the drawbacks associated with heat treatment [35]. Similarly, the convenient and problem-free application of UV light to food stocks stored in closed volumes can effectively combat airborne pathogens [36]. Over a century of scientific research has unequivocally demonstrated the efficacy of UV-C disinfection, and no alternative form of disinfection has surpassed its effectiveness [37].

2.3. Factors Influencing the Impact of UV-C Light on Foods: A Comprehensive Discussion

UV-C light is a promising technology for food preservation, offering microbial inactivation and extending shelf life. However, various factors beyond the primary parameters of frequency, distance, and intensity can influence the effectiveness of UV-C light treatment. This paper delves into these additional factors that can modulate the impact of UV-C light on foods, including product stability, ambient temperature, target product surface quality (matte vs. glossy), and others [41]. UV-C light, with its short wavelength of 200–280 nm, possesses germicidal properties, making it a valuable tool for food disinfection. While the primary parameters of frequency, distance, and intensity play crucial roles in determining the efficacy of UV-C light treatment, several other factors can significantly influence the impact of this technology on foods. Factors influencing UV-C light treatment include the following:

- Product Stability: The stability of the product during UV-C light exposure affects the treatment's effectiveness. For instance, liquid products may require agitation or continuous movement to ensure uniform exposure and prevent shadowing effects [42].
- Ambient Temperature: The ambient temperature during UV-C light treatment can influence the inactivation rate of microorganisms. Studies have shown that lower temperatures can enhance the effectiveness of UV-C light treatment [38].
- Target Product Surface Quality: The surface quality of the target product, whether matte or glossy, can affect the penetration and absorption of UV-C light. Glossy surfaces tend to reflect UV-C light, potentially reducing its effectiveness in shadowed areas [38,39].
- The Presence of Packaging Materials: Packaging materials can have an impact on UV-C light transmission and efficacy. Some materials, such as transparent plastics, allow UV-C light to pass through, while others, like metalized packaging, may block or attenuate the light [39].
- Food Composition: The composition of the food itself can affect the impact of UV-C light. Factors such as moisture content, fat content, and the presence of natural pigments can influence UV-C light absorption and efficacy [43].
- Shadowing Effects: Shadowing effects can occur due to product geometry or packaging, leading to uneven UV-C light distribution and potentially reducing treatment effectiveness [44].

Beyond the primary parameters of frequency, distance, and intensity, a range of factors influence the effectiveness of UV-C light as a promising approach for food preservation. Understanding and considering these additional factors, such as product stability, ambient temperature, target product surface quality, packaging materials, food composition, and shadowing effects, is crucial for optimizing UV-C light treatment and achieving desired outcomes in food preservation [42].

2.4. Optimizing UV-C Light Treatment Dose–Exposure Time for Food Safety

Ultraviolet-C (UV-C) light disinfection is gaining traction as a non-thermal food preservation method. However, optimizing the treatment time for effective microbial inactivation while minimizing negative impacts on food quality presents a significant challenge. The exploration of the intricate relationship between UV-C light treatment time and food safety draws upon established scientific principles and recent research findings. Traditional food preservation methods, such as heat treatment, can compromise sensory quality and nutritional value. UV-C light, with its germicidal properties, offers a promising alternative for enhancing food safety. However, the effectiveness of UV-C light treatment hinges on a crucial factor: treatment time [42,45].

1. The Dose–Response Relationship and Target Inactivation

The concept of dose, defined as the product of UV-C light intensity (mW/cm^2) and exposure time (in seconds), governs the efficacy of UV-C light disinfection [42]. The dose–response relationship dictates that microbial inactivation increases with higher UV-C light doses. This relationship often follows a logarithmic trend, where a higher dose results in a greater reduction in microbial populations [46,47]. The "Weibull model", a widely used mathematical model, can be employed to quantify this relationship, and predict the level of microbial reduction achieved for a specific UV-C light dose [48]. The Weibull model is a powerful tool for analyzing this dose–response relationship in UV-C. It can fit this mathematical equation to experimental data to predict the level of microbial reduction for a specific UV-C light dose. When applying UV-C light to inactivate microorganisms on food surfaces, the effectiveness depends on the dose. The dose is calculated by multiplying the UV-C light intensity (mW/cm^2) by the exposure time (seconds). The dose–response relationship describes how microbial inactivation increases with the UV-C light dose.

This relationship typically follows a logarithmic trend: a higher dose results in a greater reduction in the number of viable microorganisms [49]. Dose (intensity × time) is important for effective microbial inactivation, which is a key concept related to the Weibull model:

a. Probability of Survival: It estimates the probability that a single microorganism will survive a given UV-C light dose.
b. Logarithmic Reduction: It allows us to predict the number of logarithmic units (log CFU/mL) by which a microbial population will be reduced at a specific dose. (CFU stands for colony-forming unit, a measure of viable microorganisms) [49].

2.4.1. Daily UV-C Dose Application

The daily UV-C dose required for food products is determined by a variety of factors [42,43] including the following:

- Microbial load: the number and type of microorganisms present in the product.
- Package permeability: the extent to which the packaging allows UV-C light to penetrate.
- Product type: different dairy products, such as milk, yogurt, and cheese, have varying sensitivities to UV-C light.
- Desired shelf life: higher doses may be necessary for a longer shelf life.

2.4.2. General Recommendations

- Transparent-packaged dairy products: 0.5–1 kJ/cm^2 daily dose.
- Cartooned products have a daily dose of 1–2 kJ/cm^2.
- Daily dose (kJ/cm^2) = microbial load (log CFU/g) × inactivation factor × safety factor
- Microbial load (log CFU/g): initial microbial count in the product (logarithm of colony-forming units per gram).
- Inactivation factor: the UV-C treatment achieves a decimal reduction in the microbial population.
- Safety factor: an additional dose to ensure adequate inactivation and account for potential variations.

2.4.3. Effective Exposure Time Analysis in UV-C Application

Effective exposure time analysis aims to determine the necessary UV-C exposure time to achieve the desired level of microbial inactivation. This time required depends on the dose and UV-C light intensity [21,50].

- Exposure time (seconds) = dose (kJ/cm^2)/intensity (mW/cm^2)
- Dose (kJ/cm^2): UV-C dose applied to the food product
- Intensity (mW/cm^2): intensity of the UV-C light source

If a 0.5 kJ/cm^2 UV-C dose is applied and the UV-C light intensity is 10 mW/cm^2, the required exposure time is the following: exposure time (seconds) = 0.5 kJ/cm^2/ 10 mW/cm^2 = 50 s.

2.4.4. Other Factors Influencing Optimal Treatment Time

Several other factors influence the optimal UV-C light treatment dose and time for a particular food product. These factors include the following:

a. Microbial Target: Different microorganisms exhibit varying degrees of susceptibility to UV-C light. Spores, for instance, are significantly more resistant than vegetative bacterial cells [48]. As a result, the target microorganism dictates the required UV-C light dose, as well as the treatment time [30].
b. Food Product Characteristics: The composition and structure of a food product can have a significant impact on UV-C light penetration and efficacy. Factors like turbidity, fat content, and surface topography can influence light scattering and shadowing effects, potentially requiring longer treatment times for even distribution [41,48].

c. Food Quality Considerations: While UV-C light effectively inactivates microbes, prolonged exposure can lead to undesirable changes in food quality. These changes might include vitamin degradation, lipid oxidation, and the development of off-flavors [49]. Striking a balance between achieving the desired level of microbial inactivation and minimizing quality deterioration is crucial when determining the optimal treatment time.

2.4.5. Recent Advancements and Future Directions

Recent research explores strategies for optimizing UV-C light treatment time while mitigating negative impacts on food quality. These strategies include the following:

a. Pulsed UV-C light: Applying UV-C light in short pulses, with rest periods in between, can potentially enhance microbial inactivation while reducing thermal effects [51].
b. Combined technologies: Integrating UV-C light with other preservation methods, such as mild heat or modified-atmosphere packaging, might achieve synergistic effects and allow for shorter treatment times [21,50].
c. Optimizing UV-C light treatment methods: Optimization of UV-C methods for food safety requires careful consideration of various scientific principles and practical factors. Researchers and food processors can use UV-C light technology to make food safer while maintaining its quality [50] if they understand the dose–response relationship, the susceptibility of target microorganisms, and the relationship between treatment time and food quality. Continued research on novel application methods and integration with other technologies holds promise for the further refinement of UV-C light treatment for the food industry [47].

2.5. Factors Affecting UV-C Application Efficiency: Critical Parameters for Disinfection

The provided response includes Table 3, which describes the key characteristics that impact the efficacy of UV-C disinfection applications. Comprehending and enhancing these factors is crucial for attaining the dependable and uniform elimination of microorganisms in different sectors and environments. Several industries, including food processing, medical device disinfection, air and water purification, and building cleaning, utilize UV-C applications. However, the mere presence of UV-C light does not exclusively dictate the effectiveness of UV-C disinfection. Multiple factors significantly influence the extent of microbial inactivation accomplished. We can roughly classify these crucial parameters into two categories: treatment parameters and target parameters [42].

Table 3. Factors affecting UV-C application efficiency: critical parameters for disinfection when microorganism profile is unknown [39,52–54].

Critical Parameter	Description	Impact on Efficiency
UV-C Intensity (W/m^2)	The power of UV-C radiation emitted per unit area.	Higher intensity leads to faster inactivation of microorganisms.
UV-C Dose (J/m^2)	The total amount of UV-C radiation energy delivered to a target area.	Higher dose ensures more thorough inactivation of microorganisms.
Process Time (s)	The duration of UV-C exposure.	Longer exposure time allows for more effective inactivation of microorganisms.
Distance (cm)	The distance between the UV-C source and the target surface.	Shorter distance increases the intensity of UV-C radiation reaching the target.
Temperature (°C)	The ambient temperature surrounding the UV-C source and the target surface.	Some microorganisms are more susceptible to UV-C radiation.
Relative Humidity (%)	The amount of moisture in the air.	Higher humidity can reduce UV-C penetration and decrease its effectiveness.
Target Surface Characteristics	The material, texture, and topography of the surface being treated.	Smooth, non-porous surfaces allow for better UV-C penetration.
Shielding and Shadowing	Th presence of obstructions or uneven surfaces that block UV-C radiation.	Eliminate shielding and ensure uniform exposure for optimal disinfection.

2.5.1. Treatment Parameters

Treatment parameters include variables related to the UV-C source and the treatment process. The following factors should be considered: UV-C intensity, dose, exposure period, distance between the UV-C source and the target surface, ambient temperature, relative humidity, and the presence of shielding or shadowing effects. By optimizing these treatment parameters, the target surface can receive an adequate amount of UV-C radiation, effectively neutralizing germs [53].

2.5.2. The Target Parameters

Target parameters refer to the specific characteristics of the treated surface and the present microorganisms. These parameters include the surface's material, texture, and topography; the initial microbial population; the presence of biofilms; and the specific type of microorganisms targeted. Understanding these specific target factors is critical for selecting appropriate UV-C treatment parameters and forecasting disinfection effectiveness [53] to ensure that UV-C disinfection is effectively employed to achieve the desired level of microbial reduction in various settings.

2.6. Extending Shelf Life of Dairy Products: Effectiveness and Limitations of UV-C

The demand for minimally processed and extended-shelf-life dairy products has propelled the exploration of non-thermal preservation techniques like UV-C microproduct applications (air, water, surface, and food). The dairy industry is constantly seeking innovative methods to extend the shelf life of its products while maintaining quality and consumer appeal. Conventional preservation techniques, such as pasteurization and refrigeration, have limitations in terms of product quality and shelf life. UV-C microproduct applications have emerged as a promising non-thermal approach to address these challenges [52].

1. Effectiveness in Shelf-Life Extension: Studies have demonstrated the effectiveness of UV-C microproduct applications in extending the shelf life of various dairy products. For instance, studies have shown that UV-C treatment of milk can extend its shelf life by up to 53 days, while pasteurized milk alone only lasts 14 days [42]. Similarly, studies have found that UV-C treatment extends the shelf life of cheese, yogurt, and other dairy products (Table 4) [39,53,54]. Here, we present potential shelf life and UV-C effects on dairy food:

Table 4. Daily required UV-C application times for sterilization of milk and milk-derived foods [46,50,51].

Product	Milk Type/ Description	Wavelength	Intensity	Distance	Exposure Time	Additional Considerations
Fresh Milk	Refrigerated	254 nm	Medium	10–20 cm	1–2 min	Ensure clean and dry.
Raw Milk	Unpasteurized	254 nm	Medium	10–15 cm	2–3 min	Ensure clean and free of contaminants. Consult regulations and safety precautions.
Pasteurized Milk	Treated	254 nm	Medium	10–15 cm	1–2 min	Ensure clean and unopened.
Yogurt	Fermented Milk	254 nm	Medium	10–20 cm	1–2 min	Achieve smooth consistency. Stir gently after treatment.
Cheese (Hard)	Aged Cheese	254 nm	Medium	15–20 cm	3–4 min	Create a smooth surface. Rotate for even exposure.
Cheese (Soft)	Spreads, Cream Cheese	254 nm	Medium	10–15 cm	2–3 min	Achieve smooth consistency. Stir gently after treatment.
Butter	Solid Fat	254 nm	Medium	10–15 cm	2–3 min	Apply in melted or softened state.

Table 4. *Cont.*

Product	Milk Type/ Description	Wavelength	Intensity	Distance	Exposure Time	Additional Considerations
Ice Cream	Dairy Dessert	254 nm	Medium	15–20 cm	2–3 min	Ensure smooth consistency. Stir gently after treatment. May affect texture.
Whey Protein Powder	Milk Derivative	254 nm	Low	15–20 cm	3–5 min	Spread powder in thin layer. May affect flavor.

   a. Limitations and Considerations: Despite its promise, UV-C microproduct use has limitations and considerations that need to be addressed.
   b. Limited Penetration Depth: UV-C radiation has a limited penetration depth, typically a few millimeters. This restricts its effectiveness when treating bulk products or products with complex structures.
   c. Potential Impact on Food Quality: Excessive UV-C exposure may lead to vitamin degradation, off-flavors, and texture changes in dairy products [54].

2. Efficacy Against Spores: UV-C is less effective against bacterial spores, which are dormant forms of bacteria that are more resistant to environmental stresses. To extend the shelf life of UV-C applications and achieve maximum effectiveness in food products, it is important to optimize the UV-C dose and exposure time and product processing. Furthermore, UV-C's limitations, such as its inability to penetrate materials, potential adverse effects on food quality, and inability to effectively remove spores, have highlighted the need for alternative or complementary methods. Furthermore, it is important to remember that UV-C technology, while effective in the process of deactivating microorganisms and genetically preventing their proliferation in food products, does not offer permanent protection. Therefore, it should be quite necessary to continue the examination of the potential benefits of a sustainable [micro] solution for longer-term protection [38].

Table 4 provides general guidelines for UV-C light treatment in food preservation. For optimal results, it is crucial to use a UV-C treatment specifically tailored to the food type, packaging, and desired shelf life. The following recommendations are important:

- Follow safety precautions when using UV-C equipment.
- Check local regulations regarding UV-C light usage for food preservation.
- Ensure the food is clean and dry before UV-C treatment.
- Avoid direct exposure to UV-C light.
- Allow the food to cool after UV-C treatment.

3. The SLID

The global food industry faces a monumental challenge: feeding a growing population while minimizing environmental and health impacts. Each year, global food production wastes a staggering one-third of its food [7]. Current food preservation methods often rely on refrigeration, which has limitations in accessibility and energy consumption, or chemical additives, which raise concerns about long-term health effects. In this context, low-frequency ultraviolet-C (UV-C) light emerges as a promising technology for combating microbial contamination in food, offering a potent and non-toxic approach [1]. However, its efficacy is subject to limitations such as the inability to provide continuous protection, limited surface penetration, and the requirement for precise application parameters [38]. Additionally, concerns regarding potential human health risks from direct exposure exist [55].

These limitations underscore the need for a thorough evaluation of UV-C technology's benefits and limitations in enhancing food safety, improving storage conditions, and reducing household waste levels. The Smart-Lid (SLID) concept addresses these limitations by offering a targeted and controlled approach to UV-C applications. By programming a built-in UV-C light source for periodic activation, the SLID potentially reduces the need for continuous exposure (Figure 3a,b). Additionally, the lid design can facilitate deeper light penetration into exposed food surfaces compared to traditional UV-C applications. By incorporating user-friendly controls, the SLID aims to address the challenge of precise application parameters. At the household level, proposing the SLID concept as a sustainable solution or product helps overcome identified challenges while aligning with UN 2030 goals for sustainable development and the transition to a circular economy. The idea of "reducing household waste and contributing to food safety by using waste and unused packaging while reducing the potential risk to human health" serves as a promising starting point for an innovative and sustainable solution. Encouraging sustainable reuse alongside recycling at the household level constitutes a novel and innovative approach to addressing household food waste, with the potential to significantly reduce carbon emissions.

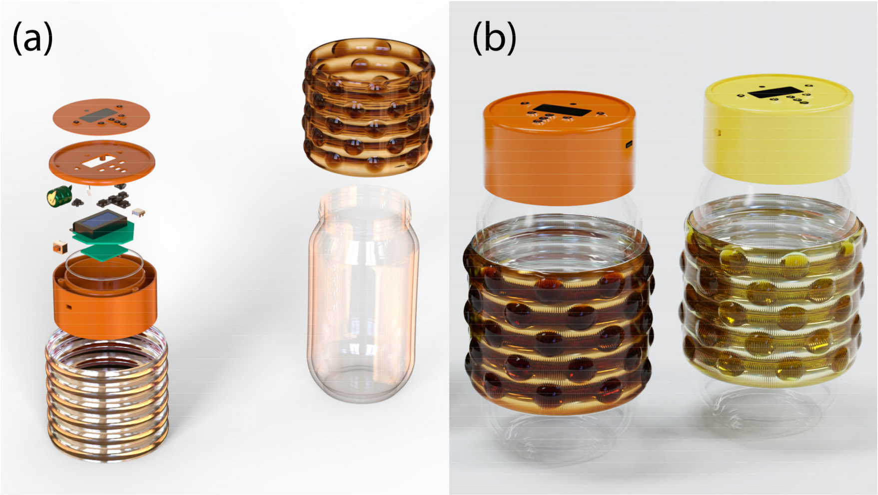

Figure 3. (**a**) The components of the SLID, (**b**) the SLID UV-C product.

3.1. The Working Principle of the SLID Project

The Smart-Lid (SLID) project (Figure 4) tackles the dual challenges of food waste reduction and household food safety through a novel and sustainable approach. Here is a breakdown of its working principle, its importance, and its impact on food safety and storage:

- UV-C Light Source: Within the SLID, a strategically positioned, wide-angle UV-C LED light source is integrated. This positioning ensures that the UV-C light reaches all food surfaces within the jar for effective microbial inactivation.
- User-Controlled Treatment: The SLID features a user-friendly interface that allows users to select pre-programmed treatment settings based on the type of food stored. These settings control the duration and intensity of the UV-C light exposure, optimizing the treatment for different food types.
- Controlled Environment: The SLID design prioritizes maintaining consistent internal conditions, including light source height and internal temperature, to ensure optimal UV-C treatment effectiveness.

3.1.1. Working Principles

1. Repurposed Glass Jar: The SLID concept utilizes readily available glass jars as storage containers. These jars are ideal for their durability, transparency, and compatibility with UV-C light (discussed later).

2. Integrated UV-C Light Source: The SLID incorporates a built-in UV-C LED (light source, 120 degrees), strategically positioned to illuminate the food contents within the jar, and to not allow a blind spot, with "0" shadow effect".
    - Enhanced UV-C Penetration: The SLID employs strategically positioned UV-C light sources and carefully selected glass materials to ensure that UV-C radiation penetrates deeply into the food volume. This maximizes the exposure of target microorganisms to the germicidal effects of UV-C, enhancing its inactivation efficacy (Figure 5).

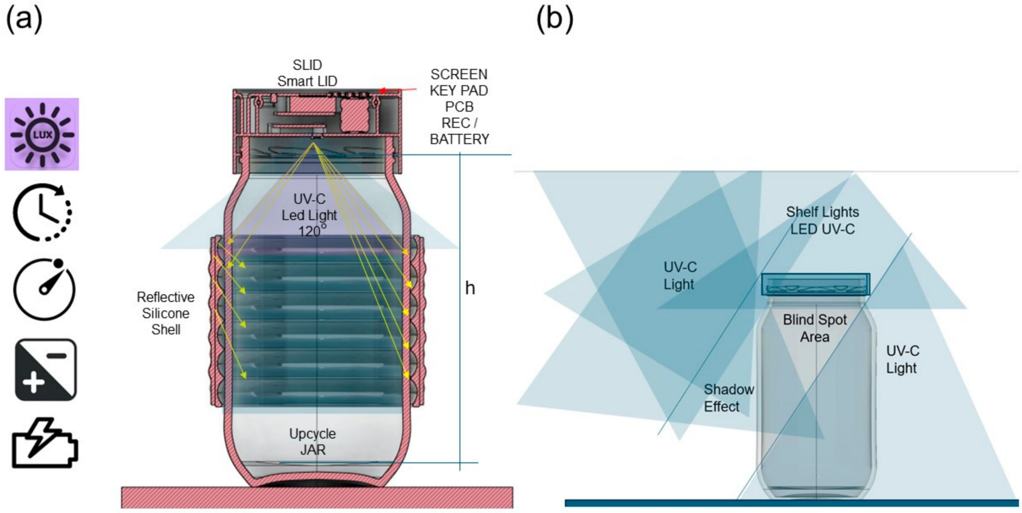

Figure 4. (**a**) The principal section of the SLID (internal UV-C LED protection), (**b**) the main challenge of retail and house-level storage with external UV-C LED protection (on shelves). The inclusion of external UV-C LED protection on shelves is the primary obstacle to retail and household-level storage. Blind spots can often be present, and they naturally have a high potential for trapping mold and causing food to deteriorate quickly. These risks can also increase where a semi-open pack is in charge during storage.

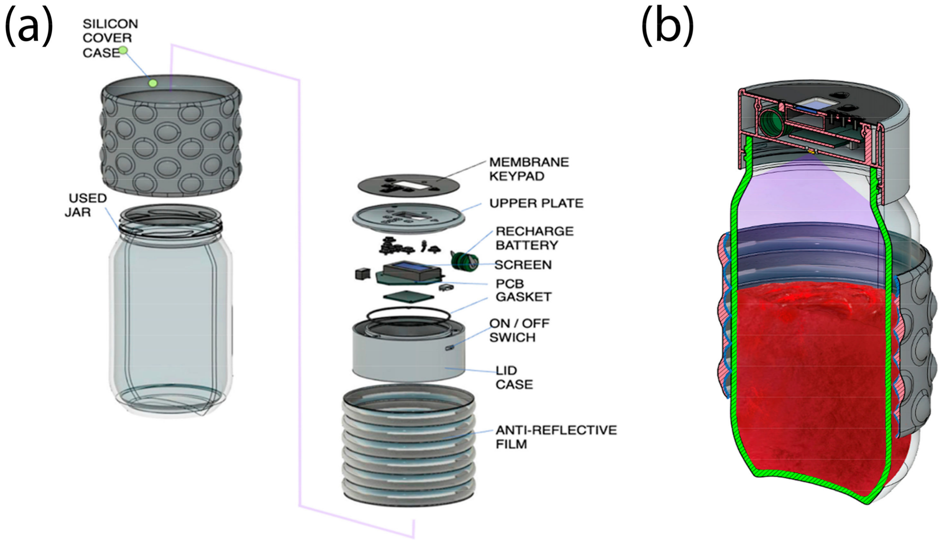

Figure 5. (**a**) Exploded presentation of SLID Smart-Lid product, (**b**) system section.

- Minimized Light Loss: The SLID incorporates anti-reflective coatings on the inner lid surface to reduce light reflection at the glass–air interface. This minimizes the loss of UV-C radiation from the jar, allowing more of the energy to reach the food and further enhancing treatment efficiency.

- Optimized Light Distribution: The SLID design considers the geometry of the jar and the placement of the UV-C light sources to achieve uniform light distribution within the food container. This ensures that all areas of the food receive adequate UV-C exposure, preventing localized microbial growth and extending shelf life.

3. Programmable Activation: The SLID features user-friendly controls that allow programming the UV-C light source for periodic activation like exposure time, operation period, and the intensity of UV-C light. This ensures targeted and controlled exposure, minimizing the need for continuous irradiation while protecting the food quality and extending its shelf life to reach the "0" waste target.
4. Food Preservation: When activated, the UV-C light emits short-wavelength ultraviolet radiation that disrupts the DNA and RNA of microorganisms present on the food surface or suspended in the air within the jar. This effectively inactivates bacteria, mold, and viruses, extending the shelf life of the food and minimizing the risk of spoilage.

3.1.2. Importance of the SLID Project

1. Reduced Food Waste: Food spoilage is a significant contributor to global food waste. The SLID project aims to combat this by extending the shelf life of opened food items, minimizing the amount of food discarded.
2. Enhanced Food Safety: Foodborne illnesses caused by microbial contamination are a major public health concern. The SLID project contributes to safer food storage by inactivating harmful microorganisms and reducing the risk of foodborne illnesses with extra air seals and moisture controls (IP68).
3. Sustainability: By repurposing existing glass jars, and with the multiple use of lids and external protective silicon covers, the SLID project promotes a circular economy, minimizing resource consumption and waste generation.

3.1.3. Impact Analysis on Food Safety and Storage

1. Food Safety: Studies have shown the effectiveness of UV-C light in inactivating a wide range of microorganisms, including bacteria, mold, and viruses [1,2]. The SLID project, by incorporating a controlled UV-C source, can significantly reduce microbial contamination on food surfaces, enhancing food safety at the household level.
2. Storage: The SLID project offers a convenient and effective solution for extending the shelf life of opened food items. By inactivating spoilage microbes, the SLID can potentially slow down the deterioration process, allowing for safer storage for longer durations.

3.2. Why Glass Jars? Embracing Sustainability in the SLID Project

The Smart-Lid (SLID) project, a revolutionary approach to household food preservation using UV-C light, stands out for its commitment to sustainability. At the heart of this commitment lies the choice to repurpose glass jars as storage containers. This decision not only aligns with the project's environmental goals but also offers a multitude of practical advantages. Repurposing glass jars for the SLID project significantly reduces the environmental impact associated with manufacturing new containers. Glass production is an energy-intensive process, consuming substantial amounts of fossil fuels and generating greenhouse gas emissions [55]. By reusing existing jars, we minimize the need for new glass production, thereby conserving resources and reducing our carbon footprint. The sustainable material properties of glass, as a material, embody sustainability principles in various aspects [56]:

a. Durability and Longevity: Glass jars are remarkably durable, withstanding repeated use and harsh environments. This durability extends the lifespan of the jars, reducing the need for frequent replacements and minimizing waste generation.
b. Recyclability: At the end of their useful life, glass jars can be readily recycled into new glass products, creating a closed-loop system that minimizes waste and promotes resource conservation.

c. Transparency: Glass jars offer excellent transparency, allowing users to easily identify and monitor the contents, reducing the likelihood of food spoilage and waste.
d. Cost-Effectiveness: Repurposing glass jars also presents economic advantages. Utilizing readily available glass jars significantly reduces packaging costs compared to purchasing new containers, making the SLID project more affordable for consumers.
e. Standardization: Glass jars come in standardized sizes and shapes, ensuring compatibility with various household storage needs and facilitating easy stacking and organization.
f. Functionality: Glass is an inert material, meaning it does not react with food or release harmful chemicals. This inertness ensures food safety and maintains the integrity of stored items. The choice of glass as the storage material for the SLID project was not merely driven by sustainability considerations; it also aligns with the project's focus on functionality. Glass exhibits unique optical properties that can enhance the effectiveness of UV-C treatment [54,57].

The decision to repurpose glass jars for the SLID project is not merely a matter of convenience; it is a testament to the project's commitment to sustainability and environmental responsibility. By embracing this approach, the solution can minimize ecological footprints, promote resource conservation, and contribute to a more sustainable future.

3.2.1. Optimizing UV-C Light Propagation in Glass Jars for Food Preservation

The effectiveness of ultraviolet-C (UV-C) light for inactivating microorganisms in food preservation applications can be significantly influenced by its propagation and reflection within the storage container. In this context, the use of a thin film placed on the outer surface of the jar lid presents a promising strategy for optimizing the efficacy of UV-C treatment while protecting human health.

3.2.2. Impact of Optical Properties on Light Propagation

The optical properties of this film can manipulate the angle at which UV-C light interacts with the glass surface, thereby influencing the reflection and transmission characteristics [58]. Anti-reflective films, for example, are specifically designed to minimize surface reflection, enabling a greater portion of the incident light to enter the glass jar [54,56]. This translates to enhanced light penetration within the container, reaching deeper into the food volume for more effective microbial inactivation.

3.2.3. Improved Efficiency and Protection

By optimizing light propagation through the film–glass interface, the overall efficiency of UV-C treatment can be significantly improved. This translates to achieving the desired level of microbial inactivation with potentially lower UV-C light exposure times or lower energy consumption. Additionally, a well-designed film can offer secondary benefits like improved user safety by minimizing UV-C leakage from the jar [59].

3.2.4. Considerations for Jar Usage

The effectiveness of UV-C treatment within glass jars is also influenced by several jar-related factors. These include the following:

1. Glass Composition: Different types of glass exhibit varying degrees of UV-C transmittance. Borosilicate glass, for instance, offers superior UV-C transmission compared to standard soda–lime glass [59,60].
2. Jar Geometry: The shape and size of the jar can affect the path length of the UV-C light within the container, impacting the uniformity of microbial inactivation. Cylindrical jars, because of their radial geometry potential, can offer more uniform light distribution compared to jars with complex geometries.
3. Food Filling Level: The volume of food present within the jar affects the distance that UV-C light needs to travel to reach target microorganisms. Optimizing the filling level can help ensure adequate light exposure throughout the food volume.

By incorporating a strategically reflective, designed film on the inner surface of the protective external part and considering jar-related factors, the effectiveness of UV-C light treatment for food preservation within glass jars can be significantly enhanced. This approach offers a promising avenue for developing safe and efficient methods to minimize food spoilage and promote food safety at the household level.

3.3. Enhancing Human Health Safety in the SLID Project: The Role of Anti-Reflective Films

The Smart-Lid (SLID) concept, a novel approach for household food preservation utilizing UV-C light, prioritizes human health safety by incorporating an anti-reflective film on the inner surface of the jar lid. This strategic design choice offers multiple benefits that minimize the risk of UV-C exposure to users [61]:

- Minimizing UV-C Leakage and Protecting Eyes: The primary function of the anti-reflective film is to reduce the reflection of UV-C light from the glass surface, effectively preventing its leakage from the jar. This feature is crucial for ensuring that the UV-C light remains confined within the jar, preventing accidental exposure to users' eyes and skin. The film's ability to enhance light transmission through the glass also contributes to this safety aspect by minimizing the need for excessive UV-C intensity, further reducing the potential for harm [59].
- Optimizing Light Penetration and Efficacy: In addition to its safety benefits, the anti-reflective film also plays a role in optimizing the efficacy of UV-C treatment. By minimizing surface reflection, the film allows more UV-C light to penetrate deeper into the food volume, ensuring more uniform microbial inactivation and reducing the risk of food spoilage. This enhanced light penetration can potentially lead to shorter treatment times or lower UV-C intensity requirements, further minimizing the risk of exposure while maintaining food safety [59,60].
- Considerations for Film Design and Implementation: The design and implementation of the anti-reflective film for the SLID project should carefully consider several factors [60].
- Film Material: The choice of film material should prioritize high UV-C transmittance, durability, and compatibility with food contact applications [61].
- Film Thickness: The optimal film thickness should be determined to balance light transmission and anti-reflective properties. A thicker film may enhance reflection reduction but could also decrease light penetration [54].
- Film Application Method: A uniform and consistent application method should be employed to ensure consistent optical performance across the film surface.

The incorporation of an anti-reflective film in the SLID project demonstrates a commitment to prioritizing human health safety while optimizing the effectiveness of UV-C treatment for household food preservation. By minimizing UV-C leakage and enhancing light penetration, the film contributes to a safer and more efficient food preservation solution.

3.4. Understanding the SLID Control Panel and Settings

Figure 6 presents the control panel of a UV-C light (SLID) food storage unit used at home. The following breakdown of the user interface is based on the image:

1. Display: The display shows the currently selected values for exposure time (hours and minutes) and UV-C intensity (low, medium, and high).
2. Controls:
    a. H (hours): This button allows you to set the exposure time in hours. You can choose between 1, 3, 6, 9, 12, and 24 h.
    b. M (minutes): This button allows you to set the exposure time in minutes. You can choose between (1, 2, 3, and 5 min).
    c. Up/down arrows for data entry: These arrows allow you to adjust the selected minute value.

   d. UV-C intensity: With this button, you can set the UV-C light intensity level (L, M, or H). You can choose between low, medium, and high.
   e. OK button: This button confirms your selections and starts the UV light sanitization process.
   f. Cancellation button: This button cancels any changes you made and returns the display to the last saved settings.

3. Using the control panel to adjust for different food types: The user manual informs the user and provides all information about recommended settings for different food types. It would likely be necessary to consult a separate user manual or consult with the manufacturer to find recommended exposure times and intensities for specific food items. Safety information: UV-C light can be harmful to human skin and eyes. When using a UV light sanitizer, it is crucial to adhere to safety precautions such as carefully placing a protective shield on the jar, wearing appropriate personal protective equipment (PPE), and avoiding exposure to the light.

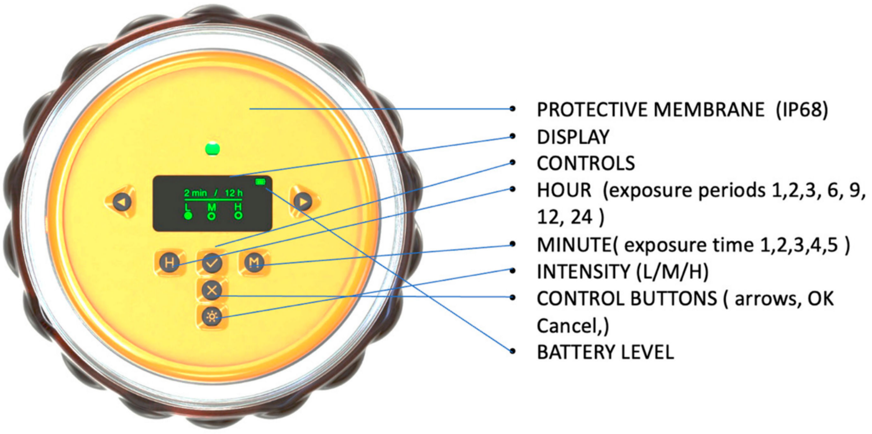

Figure 6. Control panel of SLID.

Additional notes: The effectiveness of UV light sanitization on food can vary depending on the wavelength of the light, the exposure time, and the intensity of the light. UV light sanitization may not be suitable for all food types. Some foods may be sensitive to UV light and could lose nutrients or spoil more quickly. It is important to properly clean food surfaces before using a UV light sanitizer.

3.5. Optimizing UV-C Delivery and User Interface for Enhanced Food Preservation

- Enhancing UV-C Efficacy through Strategic LED Placement and Controlled Exposure: The incorporation of a strategically positioned 120-degree wide-angle UV-C LED light source within the Smart Lid (SLID) ensures the uniform and effective irradiation of food contents. This innovative design maximizes light penetration while minimizing shadowing, guaranteeing comprehensive exposure to UV-C radiation for microbial inactivation. Moreover, the inclusion of controlled exposure time and intensity settings, accessible through the user interface, enables precise tailoring of UV-C treatment to specific food types, considering their susceptibility to microbial contamination.
- User-Friendly Interface for Personalized Food Preservation: The user interface of the Smart Lid (SLID) is characterized by its intuitive design, featuring an economical monochrome display and membrane keypad for seamless data input and user interaction. This interface empowers users to effortlessly navigate through pre-programmed menus tailored to various food categories. Each menu offers a selection of exposure time, period, and intensity settings meticulously optimized for the unique characteristics of specific food types. This personalized approach ensures that UV-C treatment is precisely tailored to individual food items, striking a balance between maximum effectiveness and minimal impact on food quality.

- Creating an Optimal Food Preservation Environment: The Smart-Lid (SLID) design prioritizes the establishment of an ideal food preservation environment by meticulously controlling factors such as light source height, internal temperature, air tightness, and moisture protection. These controlled conditions are pivotal in ensuring the consistent and efficient delivery of UV-C treatment, thereby mitigating the influence of external variables on the treatment process. Additionally, the airtight seal and moisture protection mechanisms safeguard food from external contamination and moisture loss, thereby extending its shelf life and preserving its quality.

3.6. First SLID Project Test

The first prototype test started in November 2022, and the initial SLID study was completed over a 12-month period, using a sample set that included 6 × 2 samples. The initial research included six different sample groups consisting of tomato paste (N1–SL1), mayonnaise (N2–SL2), and jams, pasta, legumes, and spices (sumac) (N6–SL6). We used organic and homemade ingredients to ensure the products were free of preservatives, and we took care to ensure there were no signs of live organisms in the dry foods. The maximum recommended usage periods and expiration dates after package opening were considered for each product's shelf life. For storage, the traditional household 85 mm 1 L mason jar group was chosen. The study involved a comprehensive analysis and evaluation, as well as a real-time shelf-life test. On the other hand, we also applied microbiological testing at 2-month intervals to detect living organisms not visible in the product groups. We conducted these studies in a different laboratory, away from the experimental setting. Group 1 consisted of samples with classic lids (N1–N6), and Group 2 had samples with Smart Lids (SL1–SL6). The N1–N3 and SL1–SL3 groups were stored under the following conditions:

In the first zone, a cold environment (E1) was established.

The temperature was between 0 °C (32 °F) and 5 °C (41 °F) [1]; around 3 °C.

The humidity was around 50–60%.

There was good air circulation in the conditioned environments, but the jars were airtight.

These conditions help to slow down bacterial growth and spoilage of foods.

In the second environment, a pantry zone (E2) was established.

The ideal temperature for a pantry is between 10 °C and 21 °C (50 °F and 70 °F); the average was around 17 °C.

The humidity was between 50% and 60%.

There was good air circulation in the conditioned environments, but the jars were airtight.

These conditions help to slow down natural bacterial growth and spoilage of food samples.

One set of samples was stored in a cold environment (E1), while the N4–N6 and SL4–SL6 groups were monitored under pantry storage conditions (E2). A daily UV dose adjustment was made for each product group (Table 4). Criteria such as humidity, temperature, and air circulation in the storage environments were kept constant. The lids of the products were positioned to prevent air entry, and they were opened once a week to check for any spoilage, which was then recorded and observed. Samples taken every two months were examined in another laboratory for pathogens, live microorganisms (they were examined for caterpillars, egg formation), etc.

The UV-treated samples showed no signs of spoilage at the end of the 1-year period. However, during the second laboratory check (4 months), the first mold formation in N1 began, and the mayonnaise and jam groups showed visible spoilage. Sumac N6 (spice group) experienced live formation and taste loss during the third check (6 months). Based on data from a second literature review on UV-treated products, this study largely confirmed the values in Table 5. However, we found that the tomato pastes and sauce groups in the experiment experienced an even shorter period. It was clearly observed that the shelf life of UV-treated products was extended, considering that no biological external factors were allowed, intensive opening and closing were not performed, and air circulation was reduced. Using real-time shelf-life tests, we did not observe changes in the SLID-treated products other than physical water loss and crust formation in the tomato paste and mayonnaise samples (SL1–SL3), and we determined that no pathogen formation occurred even after six periods (12 months). On the other hand, upon microbiological testing, we observed spoilage and mold formation in the N1 group (tomato paste group) during the second period and in the N2 group during the third period (6 months), which supports the view that the SLID effect significantly extended the shelf life of these product groups. Researchers have proven that UV treatment extends the shelf life of various food products by reducing the microbial load and preventing spoilage.

Table 5. Comprehensive storage conditions matrix/potential of UV-C microproduct use [25,62–68].

Product Group	Ideal Storage Conditions (Temperature, Light, Humidity)	Considerations for Spoilage	Potential Average Shelf Life (Before UV-C)	Potential Shelf Life (After Daily UV-C)	Considerations for UV-C Microproduct Use
Grains and cereals (e.g., rice, pasta, flour)	Cool (50–70 °F), dark, dry (less than 60% RH)	Moisture absorption, insect infestation, rancidity	12 months	18–24 months	Limited penetration depth for bulk storage, potential vitamin degradation
Nuts and seeds (e.g., almonds, sunflower seeds, chia seeds)	Cool (below 70 °F), dark, airtight containers	Rancidity due to fat content, insect infestation	3–6 months	6–12 months	Potential for flavor changes at higher doses
Dried fruits (e.g., raisins, cranberries, apricots)	Cool (below 70 °F), dark, airtight containers	Mold growth, insect infestation	6–12 months	12–18 months	Limited effectiveness against insects inside packaging
Dried legumes (e.g., beans, lentils, peas)	Cool (below 70 °F), dark, airtight containers	Insect infestation, moisture absorption, loss of texture	12–24 months	18–36 months	Limited penetration depth for bulk storage
Spices and herbs (e.g., oregano, basil, chili flakes)	Cool (below 70 °F), dark, airtight containers	Loss of flavor and potency, moisture absorption	1–2 years	1.5–3 years	Limited effectiveness for ground spices
Coffee and tea (e.g., beans, loose-leaf tea)	Cool (below 70 °F), dark, airtight containers	Loss of flavor and aroma, moisture absorption	1–2 years	1.5–3 years	Limited effectiveness for opened containers
Baking ingredients (e.g., baking powder, sugar)	Cool (room temperature), dark, airtight containers	Moisture absorption, caking	Indefinite	Indefinite (may prevent caking)	Limited effectiveness for already opened containers
Pet food (dry kibble)	Cool (below 70 °F), dark, airtight containers	Rancidity due to fat content, insect infestation	12–18 months	18–24 months	Limited penetration depth for large bags
Cookies	Cool (room temperature), airtight containers	Moisture loss (drying out), mold growth, rancidity (high-fat cookies)	1–2 weeks (opened)	2–4 weeks (opened)	Limited effectiveness for opened containers, potential impact on texture
Bakery products (breads, cakes, pastries)	Varies depending on product (see references)	Staling, mold growth, rancidity (high-fat pastries)	1–3 days (opened)	2–5 days (opened)	Limited effectiveness for opened containers, potential impact on texture
Pasta	Cool (room temperature), dark, dry (less than 60% RH)	Insect infestation, moisture absorption	1–2 years	2–3 years	Limited effectiveness against existing insect infestation, potential impact on cooking properties

The test concluded that this SLID study's focus on the fine line between staleness and spoilage could further enhance its potential, revealing significant improvements in food storage containers. In this 12-month test, we charged SLID covers twice in a cold (3 °C) environment and once in a cellar (15–18 °C). The preliminary results reveal a tendency to extend the recommended consumption periods for products after opening, a significant finding for perishable foods. For dry foods, this period tended to extend by 30–55%.

3.7. Broader Social and Economic Impact of the SLID Project: A Comprehensive Analysis

The SLID project's potential to reduce household food waste extends beyond economic benefits, creating a ripple effect with positive social and environmental implications. By promoting more sustainable food consumption practices, the SLID project contributes to a future where food resources are valued and utilized efficiently.

Quantifying the Impact: Estimating Savings and Waste Reduction

To evaluate the broader social and economic impact of the SLID project, it is crucial to quantify its potential impact on household savings, waste reduction, and overall resource utilization. While precise calculations require comprehensive data and analysis, here is a proposed approach to estimating these impacts:

- Household Savings: Studies indicate that households discard an average of 25–35% of their food purchases due to spoilage. The SLID project's ability to extend food shelf life can potentially reduce this waste by 50%, saving households an estimated 12.5–17.5% of their annual grocery expenses [1].
- Minimized Food Waste Disposal Costs: Food waste disposal costs vary by region but can range from USD 10 to USD 30 per household per year. By reducing food waste, the SLID project can help households save on these disposal costs.
- Waste Reduction and Resource Conservation: The SLID project has the potential to reduce household food waste by 50%, diverting millions of tons of food from landfills and incinerators. This reduction in food waste translates to significant savings in landfill space, energy consumption associated with waste management, and greenhouse gas emissions.
- Resource Conservation: Food production utilizes significant resources, including land, water, and energy. When food goes to waste, these resources are essentially squandered. The SLID project's contribution to food waste reduction translates to a more efficient utilization of resources across the entire food supply chain.

3.8. Household Food Waste: Formulas, Statistics, and the Impact of the SLID Project

While there is no single, universally applicable formula for determining the exact amount of food waste generated in a household, several approaches can provide estimates. Here are two common methods:

- Food Spending and Waste Reduction Percentage:

  Formula: Estimated household food waste = average annual food expenditure × waste reduction percentage

  Example: Average annual food expenditure = USD 6000, waste reduction percentage = 50%

  Calculation: Estimated household food waste = USD 6000 × 0.5 = 3000 kg

- Food Purchase Data and Waste Rate:

  Formula: Estimated household food waste = total food purchases × waste rate

  Example: Total food purchases per year = 5000 kg, waste rate = 20%

  Calculation: Estimated household food waste = 5000 kg × 0.2 = 1000 kg

Calculation Methodology: To estimate the potential savings and waste reduction on a household, annual, and waste basis, we can use the following approach:

- Household Savings: Consider the average annual household food expenditure (e.g., USD 6000) and the potential waste reduction percentage (e.g., 50%).
- Estimated Savings per Household per Year: USD 6000 × 0.5 = USD 3000
- Waste Reduction: Assume an average household generates 200 kg of food waste per year. With a 50% reduction, the estimated waste reduction per household per year would be 200 kg × 0.5 = 100 kg

- Total Savings and Waste Reduction: Extrapolating these estimates to a larger scale, such as a city or a country would provide insights into the overall economic and environmental impact of the SLID project.
- Economic Impact of Household Food Waste: The economic cost of household food waste is substantial. In the United States alone, the EPA estimates that food waste costs households between USD 161 and USD 199 billion per year. This translates to an average of USD 1560 to USD 2270 per household per year [35].
- The SLID Project's Potential Impact: The SLID project has the potential to significantly reduce household food waste by extending the shelf life of opened food items. By minimizing food spoilage, the SLID project can help households save money on food purchases and disposal costs, contributing to both economic and environmental benefits. Household food waste is a significant global issue with far-reaching economic and environmental consequences. The SLID project, by addressing food waste at the household level, offers a promising solution to reduce food loss, conserve resources, and promote more sustainable food consumption practices.

3.9. Enhancing Food Safety and Extending Shelf Life through the SLID Project

The SLID project emerges as a valuable tool for mitigating food waste and promoting food safety within households. The project's design incorporates a comprehensive storage conditions matrix that enables informed decision-making on appropriate storage methods for various dry food categories and home-sourced products. This empowers users to select the optimal storage conditions, including shelf-life recommendations, for their specific food items. By integrating UV-C light technology, the SLID project offers an additional layer of protection against microbial contamination. UV-C light effectively inactivates a broad spectrum of microorganisms, including bacteria, viruses, and mold spores, that can cause food spoilage and pose potential health risks. This targeted approach minimizes the need for chemical preservatives or excessive packaging, contributing to a more sustainable food storage system (Table 5).

- Shelf-Life Extension: The SLID project's storage conditions matrix provides valuable guidance on maximizing the shelf life of various food items through proper storage techniques. This not only reduces food waste but also ensures that food remains consumable for extended periods.
- Potential of UV-C Microproduct Use: The incorporation of UV-C light technology within the SLID provides a targeted approach to inactivating microorganisms on food surfaces, further extending shelf life and enhancing food safety.

3.10. Future Studies: Optimizing and Expanding the SLID Project

The SLID project presents a promising solution for reducing household food waste by utilizing UV-C light technology and improving storage conditions. However, further research is necessary to optimize its effectiveness and explore broader potential applications. Below, we discuss key areas for future studies.

3.10.1. Optimizing Food-Specific Treatment Regimens

a. Tailoring UV-C Doses: Research can be expanded to establish precise UV-C light exposure times and intensities optimized for different food types to ensure microbial inactivation efficacy while minimizing impacts on food quality.
b. Improving Storage Conditions: More research can be done to find out how UV-C treatment works with different storage conditions (like temperature and humidity) for different types of food. This could lead to personalized storage plans that make the SLID system's shelf-life extension work best.

3.10.2. Long-Term Food Safety and Quality Evaluation

a. Long-Term Microbial Control: To address recontamination concerns, studies can assess the long-term efficacy of UV-C treatment in controlling microbial growth on food surfaces stored within the SLID system.
b. Nutritional Value Preservation: Research can examine the impact of UV-C light exposure on the nutritional quality of various food items over extended storage periods to ensure both shelf-life extension and the preservation of nutritional quality.

3.10.3. Usability and Consumer Adoption Studies

a. User Interface Optimization: To maximize user adoption and effectiveness, evaluations can focus on user interaction with the SLID system's interface, emphasizing ease of use, clarity of instructions, and customizability of treatment settings for different food types.
b. Consumer Behavior and Acceptance: Social science research can explore consumer attitudes and perceptions towards the SLID project to identify barriers to adoption and inform strategies for promoting household use.

3.10.4. Life Cycle Assessment and Environmental Impact

a. Energy Consumption and Efficiency: Assessments can evaluate the energy consumption of the UV-C light source within the SLID and explore strategies for optimizing energy efficiency while maintaining microbial inactivation effectiveness.
b. Life Cycle Analysis: Comprehensive assessments can evaluate the SLID project's environmental impact throughout its life cycle, identifying areas for environmental footprint reduction from material sourcing to disposal.

3.10.5. Exploring Broader Applications

a. Commercial Food Storage: Research can investigate the feasibility and effectiveness of implementing the SLID system in commercial food storage settings, such as restaurants or grocery stores.
b. Beyond Food Preservation: Exploration of UV-C light's germicidal properties for disinfecting surfaces or inactivating airborne microorganisms in household settings can expand the SLID technology's applications.

Future studies can optimize the SLID project for efficacy, user-friendliness, and environmental sustainability, thereby maximizing its impact on food waste reduction and food safety.

4. Conclusions

The global landscape is rife with intricate challenges, spanning from food waste and hunger to the burgeoning issue of overflowing landfills. With approximately 17% of available food going to waste each year, totaling nearly 690 million tons, the ramifications are profound, exacerbating greenhouse gas emissions and environmental degradation. Concurrently, millions around the world grapple with food insecurity and hunger, while landfills burgeon, posing grave environmental and health hazards. Amidst this complexity, the SLID project emerges as a beacon of hope, offering a multifaceted solution poised to address these interconnected challenges. Through the strategic utilization of UV-C light technology and meticulously optimized storage conditions, the SLID stands poised to extend the shelf life of diverse food items, thereby curbing household food waste. This not only fosters environmental sustainability but also conserves vital resources, potentially mitigating issues of food insecurity.

The direct impact of the SLID's capacity to prolong food shelf life cannot be understated, as it directly mitigates household food waste, a significant global contributor to the broader issue. By curtailing spoilage and extending the period during which food remains edible, the SLID empowers households to economize on food expenditures and reduce their ecological footprint. Furthermore, by diminishing food waste, the SLID indirectly contributes to alleviating hunger and food insecurity by augmenting the availability of edible sustenance. Through shelf-life extension, the SLID endeavors to ensure that a greater proportion of food reaches those most in need, particularly in regions grappling with limited access to nutritional resources. Additionally, by mitigating food waste, the SLID alleviates the strain on landfills teeming with food remnants and other organic refuse. This not only obviates the necessity for additional landfill sites but also mitigates the associated environmental and health hazards arising from landfill overflow.

However, notwithstanding its promising potential, the SLID project is not without its challenges. To ensure widespread adoption and sustained effectiveness, concerted efforts are imperative. Key challenges include the optimization of treatment regimens for diverse food types to maximize microbial inactivation while safeguarding food quality, as well as the comprehensive evaluation of UV-C treatment's long-term efficacy in controlling microbial proliferation and preserving food's nutritional integrity within the SLID system. Moreover, enhancing the user interface of the SLID system and delving into consumer attitudes and perceptions are crucial steps towards fostering its uptake in households. A comprehensive life cycle assessment is imperative to gauge the environmental impact of the SLID project across its entire life cycle, spanning from material procurement to disposal. In essence, the SLID project represents a holistic approach towards tackling the multifaceted issues of food waste, hunger, and landfill overflow. Through the amalgamation of UV-C light technology and optimized storage conditions, the SLID holds the promise of making substantial strides towards environmental sustainability, resource conservation, and food security. Future endeavors should prioritize the refinement of treatment protocols, assurance of long-term food safety and quality, enhancement of usability and consumer acceptance, and rigorous assessment of environmental ramifications. With continued refinement and advancement, the SLID stands poised to emerge as a pivotal tool in the global fight against food waste and its attendant challenges.

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