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Development and Engineering Substantiation of a Low-voltage UV-C System for Bactericidal Sanitation of Milk-transport Containers

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Authors' contributions

This work was carried out in collaboration among all authors. Author AS conceptualized the study, developed the methodology, designed the engineering system, performed the UV-C dose calculations and electrical and energy parameter calculations, wrote the original draft, and reviewed and edited the manuscript. Author NS analyzed dairy-processing and sanitation conditions, conducted the literature review, edited the language, formatted the manuscript, and prepared the manuscript. Author BY analyzed UV-C electrotechnical applications, provided technical consultation, assessed electrical safety, and revised the manuscript. All authors read and approved the final manuscript.

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Abstract

Background: Hygienic preparation of milk-transport containers is important for limiting secondary contamination after washing and before filling.
Aims: This study aims to develop and substantiate a compact low-voltage ultraviolet-C (UV-C) electrotechnical system for finishing bactericidal sanitation of milk-transport containers and to define its constructive, electrical, operating and safety parameters.
Study Design: Engineering development, analytical calculation and safety-oriented substantiation of a prototype sanitation device.
Place and Duration of Study: The study was conducted at Poltava State Agrarian University, Poltava, Ukraine, and Poltava Academy of Sciences of Technological Cybernetics of Ukraine, Poltava, Ukraine, during the development, engineering substantiation and manuscript preparation of the prototype in 2024-2026.
Methodology: A portable low-voltage UV-C unit was developed for treatment of the internal air volume and accessible inner surfaces of previously washed and drained containers used for milk and dairy-product transportation. The study combined engineering design analysis, electrical calculation, UV-C dose modelling, estimation of energy consumption and safety assessment. The UV-C dose was formalised as the product of average irradiance and exposure time. Microbiological validation and irradiance mapping were not performed at this stage; these procedures are proposed as mandatory steps before industrial implementation.
Results: The developed unit is intended for a treated volume of up to 5 m^3 and has overall dimensions of 550 x 160 x 160 mm, a mass of 3 kg and an installed electrical power of 20 W. The device can be supplied from 12 or 24 V DC sources, with estimated current consumption of approximately 1.67 A and 0.83 A, respectively. For a maximum treated volume of 5 m^3, the specific installed power is 4 W/m^3. The calculated energy consumption of one sanitation cycle is 1.67 Wh for 5 min, 3.33 Wh for 10 min, 5.00 Wh for 15 min and 6.67 Wh for 20 min.
Conclusion: The proposed system can be considered as a finishing reagent-free sanitation step after mechanical washing, detergent cleaning, rinsing and draining. It is not a substitute for standard cleaning procedures. Since no experimental microbial-reduction data are presented in this manuscript, its expected function is limited to an engineering hypothesis that must be confirmed by UV-C irradiance measurements and microbiological surface swab testing at selected exposure times.

Keywords: UV-C irradiation; milk transportation; transport container; bactericidal sanitation; food contact surface; electrotechnical system; low-voltage UV-C unit.

1. Introduction

Milk is a nutrient-rich raw material and a favourable medium for the growth of spoilage and pathogenic microorganisms. Its hygienic quality during transportation depends not only on the initial microbiological condition of the product but also on the sanitary condition of containers, lids, internal surfaces, the air volume, and handling equipment. Even after routine washing, residual microorganisms may remain in scratches, joints, seals, or poorly drained areas. These contamination sources may contribute to secondary microbial contamination and accelerate the increase in milk acidity during transportation and short-term storage. Dairy-focused literature also indicates that microbial safety risks may extend across the farm-to-fork continuum, which supports the need for hygienic controls at handling, transportation and processing stages (Saha et al., 2026).

Traditional sanitation of milk containers is based on mechanical cleaning, detergent washing, rinsing, thermal treatment and chemical disinfectants. These methods are essential and cannot be eliminated; however, they require water, energy and chemical reagents. In small farms and milk-collection points, deviations from a stable cleaning regime may occur due to limited equipment, irregular container turnover and human factors. For this reason, additional non-thermal and reagent-free methods of finishing sanitation are of practical interest. Recent evidence from milk-processing companies further shows that cleaning programmes and cross-contamination control systems are treated as components of good manufacturing practice in dairy operations (Lilian et al., 2023).

Ultraviolet light has been widely discussed as a non-thermal technology in dairy processing. It can be used for microbial inactivation in air, water, packaging materials and food-contact surfaces (Koca et al., 2018; Chawla et al., 2021). UV-C radiation is particularly effective in the wavelength range of 200-280 nm; radiation near 254 nm is commonly associated with the maximum germicidal effect of low-pressure mercury sources because of strong DNA absorption (Koca et al., 2018). The mechanism of microbial inactivation is associated with photochemical damage to nucleic acids and inhibition of replication (Koca et al., 2018; Sharma et al., 2023). A recent review of UV-C treatment in food and food-surface applications indicates that processing parameters, microbial characteristics and food or surface properties must be considered when defining UV-C treatment conditions (Ramos et al., 2024).

The use of UV-C for food-contact surfaces differs from the direct treatment of milk. In liquids such as milk, low penetration depth, turbidity and possible quality changes must be considered (Chawla et al., 2021; Matak et al., 2005). In the present work, the product itself is not irradiated. The target is the internal volume and accessible inner surfaces of transport containers before filling with milk. This approach is technologically safer because it avoids direct photo-oxidative action on the product and focuses on preventing post-washing contamination from the container. Recent work on deposited bioaerosols on food-contact surfaces showed that UV-C LED treatment can reduce microbial contamination, but the reduction may differ among surface materials (Sharma et al., 2025).

The effectiveness of UV-C treatment is governed by the radiation source, wavelength, dose, distance to the treated surface, exposure time, surface cleanliness, geometry, shadows and target microorganisms (Koca et al., 2018; Sharma et al., 2023; Galié et al., 2018). For this reason, engineering design of UV-C devices for transport containers must combine electrical parameters, mechanical arrangement, safety interlocking and an irradiation-dose model. The device should be compact, easy to insert into the container, safe for personnel, and compatible with existing washing and preparation operations (International Organization for Standardization, n.d.; Lelieveld et al., 2016). Experimental and simulation-based work with a 254 nm UV-C enclosure has shown that spatial fluence distribution can vary within a treatment unit, supporting the need for geometry-specific dose assessment in device design (Chen et al., 2023).

For milk-transport containers, UV-C treatment should be regarded as a finishing bactericidal stage applied to an already washed and drained internal surface. This technological position is important because ultraviolet radiation acts mainly in line-of-sight conditions: it is highly effective for open irradiated areas, but its action is reduced by residual organic films, deposits, droplets, surface roughness and shadowed zones (Sharma et al., 2023; Galié et al., 2018). Therefore, the engineering problem is not only to select a lamp of sufficient rated power, but also to provide a rational arrangement of the UV source, controllable exposure time, reproducible positioning of the irradiator inside the container and safe electrical operation.

Previous studies by the authors formed the scientific and engineering basis for the present development. A comprehensive approach to the evaluation of ultraviolet disinfection systems was proposed by taking into account maintenance, spectral and operational coefficients that influence the delivered bactericidal dose during real operation (Semenov et al., 2026). The useful service life of ultraviolet lamps in electrotechnical systems was also analysed on the basis of the decrease in UV radiant flux during operation, which is essential for selecting replacement intervals and preventing under-dosing (Semenov et al., 2024a). In addition, the photobiological risk associated with ultraviolet lamps in electrical systems was assessed, confirming the need for interlocks, shielding and organisational safety measures when such devices are used in production environments (Semenov et al., 2024b).

The practical applicability of ultraviolet treatment for reducing microbiological contamination was also demonstrated in the disinfection of activated carbon, where UV radiation and combined UV-ozone treatment were considered as physical methods of microbial inactivation (Semenov et al., 2019). Although the object of treatment in the present work is different, the general methodological principle is similar: the technological effect is determined by the delivered UV dose, exposure conditions, irradiation geometry and the state of the treated surface.

The relevance of the proposed low-voltage UV-C system is determined by the need for compact, low-power and mobile equipment that may be used directly at farms, milk collection points and small food-processing facilities as an additional finishing sanitation step. Such equipment is expected to reduce the risk of secondary contamination of milk after washing of transport containers, but this assumption requires confirmation by measured irradiance data and microbiological validation. The system must not be presented as a chemical method for neutralising milk acidity; its possible role is preventive and is related to suppressing residual microflora on accessible container surfaces. However, the available literature does not provide sufficient engineering-focused information on compact low-voltage UV-C units designed specifically as finishing sanitation devices for empty milk-transport containers, particularly with respect to container placement, dose modelling, electrical operation and safety control.

The aim of this work was to develop and analytically substantiate a compact electrotechnical UV-C system for bactericidal sanitation of milk-transport containers, to define its constructive and electrical-functional scheme, and to relate the design parameters of the unit to maintenance, spectral, operational and safety factors of ultraviolet electrotechnical systems. The study is limited to engineering substantiation; direct microbiological validation and irradiance mapping are proposed as subsequent mandatory stages.

2. Materials and Methods

2.1 Design Object and Research Approach

The object of the study was a compact electrotechnical ultraviolet-C system intended for finishing bactericidal sanitation of milk-transport containers. The developed prototype was designated as UBZTT-20. According to the technical specification, the unit is intended for the treatment of internal air volume and accessible inner surfaces of previously washed and drained containers used for milk and dairy-product transportation. The recommended treated volume is up to 5 m^3, the installed electrical power is 20 W, the overall dimensions are 550 x 160 x 160 mm, and the mass is 3 kg.

The methodological approach was based on the combination of engineering design analysis, UV-C dose calculation, estimation of electrical energy consumption, assessment of operating conditions, and substantiation of safety requirements. This approach corresponds to the general principles of UV application in dairy processing, where ultraviolet radiation is considered suitable for air, water, packaging materials and food-contact surfaces, but its efficiency depends on dose, exposure time, surface cleanliness and irradiation geometry.

2.2 Prototype Description

The developed prototype was designed as a portable low-voltage device for use at farms, milk collection points, small dairy-processing facilities and transport-preparation areas. The unit consists of a UV-C bactericidal source, a protective quartz sleeve, a carrier frame, end caps, electrical connections, a power-supply and control unit, a timer, indication elements and safety interlocking. To avoid a product-like tone, the designation UBZTT-20 is used only as an internal prototype identifier.

The device can be powered from a 12 V or 24 V DC source. At the installed electrical power of 20 W, the estimated current consumption is approximately 1.67 A at 12 V and 0.83 A at 24 V. The source is specified as a germicidal UV-C source with a dominant wavelength near 253.7 nm, installed inside a protective quartz sleeve. The exact UV-C radiant output, lamp ageing factor and spectral power distribution were not measured in this stage and therefore are not used as experimental results; for practical implementation they should be verified using manufacturer data and radiometric measurements.

2.3 Sanitation Procedure

The proposed UV-C treatment was considered only as a finishing sanitation stage and not as a replacement for mechanical washing or detergent cleaning. Before UV-C exposure, the container must be emptied of milk residues, washed with an accepted detergent procedure, rinsed and drained. This requirement is essential because organic residues, fat films, protein deposits, water droplets and surface contamination can absorb or shield UV-C radiation and reduce the bactericidal effect.

The recommended operating sequence was as follows: removal of residual milk from the container; mechanical washing and detergent cleaning; rinsing and draining of the container; placement of the UBZTT-20 unit inside the container; closing or shielding of the treated volume; activation of the UV-C source for the selected exposure time; automatic shutdown after the sanitation cycle; removal of the unit and preparation of the container for milk filling.

Such an approach is consistent with studies showing that UV-C treatment can be used as an additional sanitation method after routine cleaning practices in the food industry, especially for food-contact surfaces.

2.4 UV-C Dose Calculation

The main calculated parameter of the sanitation process was the delivered UV-C dose. For a surface element receiving average irradiance, the UV-C dose was determined by:

$$D = E \cdot t \quad (1)$$

where D is the UV-C dose, J/m^2; E is the average irradiance at the target surface, W/m^2; and t is the exposure time, s.

The required exposure time is therefore:

$$t = \frac{D}{E} \quad (2)$$

In microbiological studies, UV-C dose is often expressed in mJ/cm^2. The conversion used in this work was: 1 mJ/cm^2 = 10 J/m^2.

For practical application, the calculated dose should be assessed at the least-irradiated accessible surface zone of the container. This is necessary because the real irradiance inside a container is not uniform and depends on the distance from the UV-C source, lamp orientation, surface geometry, shadowed areas, reflectivity of internal surfaces and contamination of the protective sleeve.

2.5 Electrical and Energy Parameters

The specific installed power of the UBZTT-20 unit was calculated as:

$$p_v = \frac{P}{V} \quad (3)$$

where p_v is the specific installed power, W/m^3; P is the installed electrical power, W; and V is the recommended treated volume, m^3.

For P = 20 W and V = 5 m^3, p_v = 4 W/m^3.

The electrical energy consumption for one sanitation cycle was calculated as:

$$W = P \cdot \tau \quad (4)$$

where *W* is electrical energy, Wh; *P* is installed electrical power, W; and τ is cycle duration, h.

For sanitation cycles of 5, 10, 15 and 20 min, the calculated energy consumption was 1.67, 3.33, 5.00 and 6.67 Wh, respectively. These values indicate that the energy demand of the proposed system is low, while the effectiveness of the treatment is primarily determined by the delivered UV-C dose, exposure geometry and surface cleanliness.

2.6 Microbiological Validation Procedure

For further validation of the developed UBZTT-20 system, microbiological control should be carried out using surface swab tests. The recommended control points are: before washing; after washing and rinsing; after UV-C treatment for 5 min; after UV-C treatment for 10 min; and after UV-C treatment for 15 min.

The main microbiological indicator may be the total microbial count on the inner surface of the container, expressed as CFU/cm^2. If necessary, additional tests may include coliform bacteria, yeasts, moulds or selected indicator microorganisms relevant to dairy hygiene.

The reduction efficiency may be calculated as:

$$R = \frac{N_0 - N}{N_0} \cdot 100 \quad (5)$$

where R is microbial reduction, %; N_0 is the initial microbial count before UV-C treatment, CFU/cm^2; and N is the microbial count after UV-C treatment, CFU/cm^2.

The logarithmic reduction may be calculated as:

$$LR = log_{10}\left(\frac{N_0}{N}\right) \quad (6)$$

where LR is log reduction; N_0 is the initial microbial count before UV-C treatment, CFU/cm^2; and N is the microbial count after UV-C treatment, CFU/cm^2. This indicator is widely used to compare the effectiveness of disinfection methods.

2.7 Safety Assessment

The safety assessment of the low-voltage UV-C unit system was based on the need to prevent direct exposure of the operator to UV-C radiation. UV-C radiation can be hazardous to the eyes and skin; therefore, the unit should include technical and organisational safety measures. These include a timer, operation indicator, emergency shutdown, electrical insulation, moisture protection of connectors, overcurrent protection, reverse-polarity protection and an interlock preventing operation when the container is open or when the unit is not fixed in the correct working position.

The device should be integrated into sanitation standard operating procedures and food safety management practices. ISO 22000 defines requirements for food safety management systems and is applicable to organizations in the food chain regardless of size or position in the chain.

2.8 Experimental Validation Plan

Since the present article focuses on engineering development and analytical substantiation of the prototype, microbiological validation is not presented as a completed result and should be considered as the next stage of the research. The proposed validation procedure includes comparative surface swab testing before washing, after washing and after UV-C treatment at different exposure times. Such testing will allow the determination of the additional bactericidal effect provided specifically by the UV-C finishing stage.

3. Results and Discussion

3.1 Design Concept of the UBZTT-20 Unit

A prototype unit for bactericidal sanitation of transport containers, designated UBZTT-20, was developed for use in the food industry during the transportation of milk and dairy products. The device is intended to reduce residual microbial contamination of milk-transport containers after routine washing and before filling. This is important because microorganisms may remain on internal surfaces, in joints, seals, scratches, and poorly drained areas of containers. These residual contamination sources can contribute to secondary microbial contamination of milk and may accelerate the increase in acidity during transportation and short-term storage.

The prototype is a compact mobile electrotechnical device designed for finishing UV-C sanitation of the internal air volume and accessible inner surfaces of transport containers. According to the prototype specification, the recommended treated volume is up to 5 m^3, the overall dimensions are 550 × 160 × 160 mm, the mass is 3 kg, and the installed electrical power is 20 W. The unit can be powered from a low-voltage 12 V or 24 V DC source. At the installed electrical power of 20 W, the estimated current consumption is approximately 1.67 A at 12 V and 0.83 A at 24 V. This low-voltage supply option increases the mobility of the system and allows its use in stationary food-processing facilities, farms, milk-collection points, and transport conditions where a standard industrial power supply may not be available.

Fig. 1. General view of the UBZTT-20 bactericidal sanitation unit for transport containers

The general view of the developed prototype is shown in Fig. 1. The device has an elongated configuration that enables its placement inside milk cans, tanks, or other transport containers, provided that the UV-C source is positioned without direct contact with the product. Such a design makes it possible to irradiate the accessible internal volume and open inner surfaces of the container after washing and draining.

Table 1. Technical characteristics of the UBZTT-20 unit

Parameter	Value
Type designation	UBZTT-20
Functional purpose	Bactericidal sanitation of transport containers
Recommended treated volume	up to 5 m³
Overall dimensions	550×160×160 mm
Mass	3 kg
Installed electrical power	20 W
Supply voltage	12 or 24 V DC
Estimated current at 12 V	approximately 1.67 A
Estimated current at 24 V	approximately 0.83 A
UV-C source type	Germicidal UV-C source in protective quartz sleeve
Dominant germicidal wavelength	near 253.7 nm
UV-C radiant output	Not measured in the present stage; to be verified by manufacturer data and radiometry
Irradiance mapping	Required before practical implementation
Microbiological validation	Not performed in the present stage; surface swab testing is required

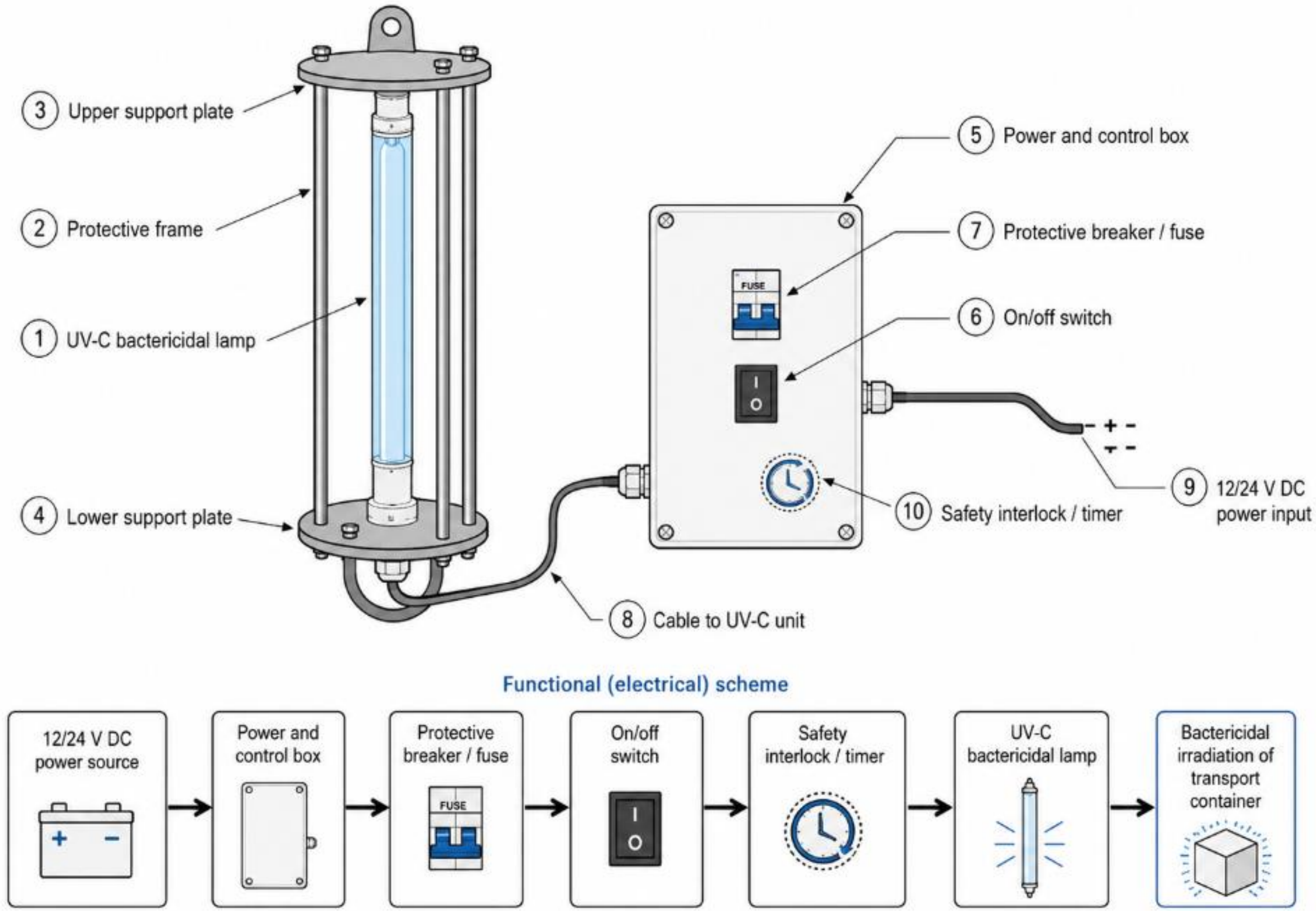

Fig. 2. Constructive and electrical-functional scheme of the low-voltage UV-C unit

The constructive and electrical-functional arrangement of the prototype is presented in Fig. 2. The figure reflects the main components of the system, including the UV-C bactericidal source, protective quartz sleeve, carrier frame, low-voltage power-supply unit, control elements, timer, operation indicator, and safety interlock. The proposed arrangement is aimed at ensuring stable exposure conditions, reproducible positioning of the UV-C source, and safe operation during sanitation cycles.

The principal technical characteristics of the prototype are summarised in Table 1.

Structurally, the unit includes a UV-C bactericidal source positioned inside a protective tubular zone, carrier elements, end caps, electrical connections, and a power-supply/control unit. The longitudinal arrangement of the radiation source is suitable for insertion into elongated tanks, milk cans or container necks, provided that the lamp can irradiate the internal volume without mechanical contact with the product. The mass of 3 kg makes the system suitable for portable use.

From the process viewpoint, the UBZTT-20 unit should be applied only after the container has been cleaned of milk residues, washed and drained. This requirement is important because dirt, fat, protein films and milk stone can absorb or block UV-C photons and protect microorganisms. Literature on UV applications in dairy processing emphasizes that the effectiveness of ultraviolet treatment depends on direct exposure, surface cleanliness, irradiation dose, exposure time and the absence of obstacles between the source and the treated surface (Koca et al., 2018; Chawla et al., 2021). Therefore, the developed unit should be considered an additional finishing bactericidal stage after washing, not a substitute for mechanical cleaning or detergent sanitation.

UV-C radiation is widely discussed as a non-thermal method for microbial inactivation in the food and dairy industries. It can be used for the treatment of air, water, packaging materials and food-contact surfaces (Koca et al., 2018; Chawla et al., 2021). For food-contact surfaces, UV-C LED devices have also been shown to provide microbial reduction, but the achieved result strongly depends on dose, surface condition and exposure geometry (Sharma et al., 2023). This is consistent with the technological role of the UBZTT-20 unit, which is aimed at sanitation of empty containers rather than direct irradiation of milk.

The use of UV-C treatment for empty milk-transport containers differs from direct UV treatment of milk. In liquids such as milk, low penetration depth, turbidity and possible changes in product quality must be considered (Chawla et al., 2021; Matak et al., 2005; Vashisht et al., 2022). In the present design, the product itself is not irradiated. The target is the internal air volume and accessible surfaces of the container before filling. This approach is technologically safer because it avoids direct photo-oxidative action on milk and focuses on preventing post-washing contamination from the container.

Thus, the proposed UBZTT-20 unit is positioned as a compact, low-power and mobile electrotechnical system for finishing sanitation of milk-transport containers. Its application may reduce the risk of secondary contamination of milk after washing of the container, while avoiding excessive use of chemical disinfectants. At the same time, the system should not be considered a chemical method for neutralising milk acidity. Its role is preventive: it suppresses residual microflora on container surfaces and may therefore slow microbiological processes that contribute to acidity increase during transportation and storage.

3.2 Irradiation-Dose Model

The delivered UV-C dose is the key parameter used to characterise the sanitation effect of the proposed system. For an elementary surface area exposed to average irradiance E, the accumulated dose D is determined according to Eq. (1). Accordingly, the exposure time required to obtain a specified target dose can be calculated using Eq. (2).

These equations provide a convenient basis for preliminary engineering calculations; however, their direct application requires consideration of the actual geometry of the treated container. Under real operating conditions, irradiance is distributed unevenly over the internal surfaces. It decreases with increasing distance from the radiation source and is affected by the orientation of the UV-C lamp, the shape of the container, shadowing from structural elements, necks, handles, joints, or internal fittings. Therefore, when selecting the sanitation mode, the delivered dose should be evaluated for the least-irradiated accessible surface area. If this zone receives lower irradiance than the average design value, the exposure time calculated by Eq. (2) must be increased accordingly.

In the proposed design, such correction is associated with the maintenance, spectral and operational coefficients used for the comprehensive assessment of ultraviolet disinfection systems (Semenov et al., 2026). Therefore, the rated electrical power of the UV-C source alone cannot be considered a sufficient indicator of bactericidal efficiency. The actual irradiance should be periodically monitored during operation, especially after prolonged lamp use, contamination of the protective quartz sleeve, or changes in the reflective properties of the internal container surfaces.

For the prototype, the specific installed power was calculated using Eq. (3). At a rated electrical power of P = 20 W and a maximum recommended treated volume of V = 5 m³, the value of p_v is 4 W/m³. This parameter does not describe the real UV-C fluence at each point inside the container, but it is useful for comparing devices designed for different treated volumes.

The electrical energy consumption for one sanitation cycle was determined according to Eq. (4). The calculated values of electrical energy consumption for different sanitation cycle durations are presented in Table 2.

Table 2. Calculated electrical energy consumption of one UBZTT-20 sanitation cycle

Cycle duration, min	Cycle duration, h	Power, W	Energy, Wh
5	0.083	20	1.67
10	0.167	20	3.33
15	0.250	20	5.00
20	0.333	20	6.67

The results indicate low electrical energy consumption by the proposed device: even a 15 min sanitation cycle requires only approximately 5 Wh. The technological effect is therefore not limited by energy cost; rather, it is determined by correct positioning of the source, sufficient dose, absence of shadow zones and stable operating procedures.

For engineering design, the exposure time can be selected using the target dose and measured irradiance. In the present manuscript, the following values are illustrative calculation examples rather than measured results. For example, if the minimum measured irradiance at the least-illuminated inner surface is 2.0 W/m2 and the target finishing dose is 400 J/m2, the exposure time should be 200 s. If the minimum irradiance decreases to 1.0 W/m2 because of increased distance or shadowing, the exposure time must be increased to 400 s. This illustrates why fixed nominal power alone is insufficient for validating a UV-C sanitation process.

Food-contact surface studies demonstrate that UV-C devices can provide substantial microbial reductions, but the achieved result strongly depends on dose and surface conditions (Sharma et al., 2023; Galié et al., 2018). Therefore, for industrial implementation of UBZTT-20, a validation protocol should include microbiological swab tests before washing, after washing and after UV-C treatment. This will allow the determination of the additional log reduction attributable specifically to the UV-C finishing step.

3.3 Operating Algorithm and Safety Requirements

The recommended sanitation algorithm is as follows: 1 - remove residual milk from the container; 2 - wash the internal surfaces using an accepted detergent procedure; 3 - rinse and drain the container; 4 - place the UBZTT-20 unit in the working position; 5 - close or shield the treated volume; 6 - activate the UV-C source for the selected exposure time; 7 - automatically switch off the source after the cycle; 8 - remove the device and use the container for milk transportation.

The possibility of operation from 12 V or 24 V DC power sources increases the practical applicability of the UBZTT-20 unit. In stationary operation, the unit may be connected through a stabilised low-voltage power supply. In mobile conditions, it may be powered from an autonomous battery or the electrical system of a vehicle, provided that the voltage, current and protection requirements of the UV-C module are met.

For safe operation, the low-voltage supply circuit should include overcurrent protection, reverse-polarity protection and reliable insulation of electrical connections. When the device is used in humid environments after washing of containers, all electrical connectors should be protected against moisture ingress, and the control unit should be placed outside the direct wet zone. The use of 12 V or 24 V supply reduces electrical risk for the operator, but it does not eliminate the need for protection against UV-C exposure.

Because UV-C radiation is hazardous to the eyes and skin, the system must include engineering controls preventing direct exposure of the operator. The control circuit should include an interlock preventing lamp operation when the container is open or the device is not fixed in the correct position, a timer, clear operation indication and emergency shutdown. These requirements are consistent with the previously analysed danger of using ultraviolet lamps in electrical systems, where photobiological safety was shown to be a key condition for practical application of UV equipment (Semenov et al., 2024b).

In the context of food safety management, the UBZTT-20 unit can be integrated into prerequisite programmes and sanitation standard operating procedures. ISO 22000 specifies food safety management system requirements for organizations in the food chain and requires the control of food safety hazards (International Organization for Standardization, n.d.). The developed UV-C device can therefore be considered a technical measure within the sanitation-control system, provided that it is validated, documented and periodically monitored.

3.4 Limitations of the Present Study

The present study should be interpreted as an engineering-development and analytical-substantiation paper. It does not report completed microbiological experiments, surface swab results, irradiance mapping or operator-exposure measurements. Therefore, statements about microbial reduction and limitation of secondary contamination are formulated as expected effects that require experimental confirmation.

Before practical implementation, the prototype should be validated by measuring UV-C irradiance at representative and least-irradiated zones inside typical milk-transport containers, determining lamp ageing and protective sleeve contamination factors, performing surface swab tests before washing, after washing, and after UV-C exposure, and verifying interlock, shielding, moisture protection, and operator-exposure control under realistic sanitation conditions.

Therefore, the reported energy parameters should not be interpreted as direct evidence of bactericidal efficiency, because UV-C irradiance distribution inside real containers was not experimentally measured in this study.

4. Conclusion

A compact low-voltage UV-C electrotechnical system for finishing bactericidal sanitation of milk-transport containers was developed and substantiated. The proposed UBZTT-20 unit is intended for the treatment of previously washed and drained containers before filling with milk or dairy products.

The developed unit has an installed electrical power of 20 W, overall dimensions of 550×160×160 mm, a mass of 3 kg and a recommended treated volume of up to 5 m^3. The possibility of operation from 12 V or 24 V DC power sources increases the mobility of the system and allows its use at farms, milk collection points, small dairy-processing facilities and transport-preparation areas.

The UV-C dose calculation was formalised using the relationship between irradiance and exposure time. For the maximum treated volume of 5 m^3, the specific installed power of the unit is 4 W/m^3. The calculated electrical energy consumption for one sanitation cycle is 1.67 Wh for 5 min, 3.33 Wh for 10 min, 5.00 Wh for 15 min and 6.67 Wh for 20 min. These values characterise the electrical and calculated design parameters of the unit, not the experimentally achieved microbial reduction.

The proposed UV-C treatment should be considered as a finishing reagent-free sanitation step after mechanical washing, detergent cleaning, rinsing and draining. It is not a substitute for standard cleaning procedures, because the bactericidal effect of UV-C radiation depends on surface cleanliness, exposure geometry, irradiation dose, distance from the source and the absence of shadowed zones.

For practical implementation, microbiological validation and irradiance mapping of the unit are required. Validation should include surface swab tests before washing, after washing and after UV-C treatment at different exposure times, together with measurements of UV-C irradiance in the least-irradiated accessible zones. This will make it possible to determine the additional microbial reduction provided specifically by the UV-C finishing stage and to establish recommended operating modes for different types of milk-transport containers.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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