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Design and Development of a Three-Stage Fruit Sanitization System (Spray–UV–Ozone)

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Abstract:

The rising concern for food safety and hygiene has significantly increased the demand for efficient and affordable fruit and vegetable sanitization systems. Existing solutions available in the market are often expensive, complex in design, and require skilled labor for operation. Additionally, these systems consume substantial amounts of water and energy while occupying large installation space. Most commercially available machines are imported, leading to higher procurement and maintenance costs. To overcome these limitations, this project proposes the design and development of a compact, cost-effective, and user-friendly fruit sanitization machine. The system is specifically tailored for small-scale industries and domestic applications, ensuring accessibility and ease of use. The proposed machine incorporates a three-stage sanitization process consisting of UV sterilization, mist-based cleaning, and ozone (O_3) purification. The UV stage effectively eliminates harmful microorganisms, while the mist cleaning system removes surface contaminants with minimal water consumption. Furthermore, ozone treatment aids in degrading pesticides and chemical residues without affecting the nutritional quality of the produce. The overall design emphasizes low power consumption, simplicity, and adaptability to alternative energy sources, offering a sustainable and eco-friendly solution for enhancing food safety standards.

Keywords —**Fruit Sanitization, UV Sterilization, Ozone Cleaning, Mist Washing, Food Safety, Sustainable Design, Small-Scale Machine, Eco-Friendly Technology**

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1. INTRODUCTION

Food safety has become a critical concern due to increasing awareness of health and hygiene among consumers. Fruits and vegetables are often contaminated with dust, pesticides, bacteria, and other harmful substances during cultivation, handling, and transportation. Traditional washing methods are insufficient to completely remove these contaminants. Moreover, existing fruit washing machines are costly, bulky, and not suitable for small-scale users or household applications. Therefore, there is a need to develop an economical, compact, and efficient fruit sanitization system.

There are attractive opportunities for entrepreneurs in the field of fruit and vegetables processing in India. The installed capacity of fruit and vegetable processing industries has increased from 21 lakh tones in 1979 to 22 lakh tones in 2009. The production of processed fruits and vegetables in India has increased from 9.8 lakh tones in 1999 to 9.9 lakh tones in 2002. An attempt was made by to develop a small-scale carrot washer for research sample purpose.

2. PROBLEM STATEMENT

Conventional fruit cleaning machines are associated with high cost, complex operation, and excessive consumption of water and energy. Their dependency on skilled Labor and large installation space limits their usability in small industries and domestic settings. Additionally, imported machines increase overall ownership cost due to expensive maintenance and spare parts. Hence, a simplified and cost-effective solution is required to ensure safe and hygienic food processing.

3. OBJECTIVES

The main objectives of this research are:

- To design and develop a cost-effective and compact fruit sanitization machine suitable for small-scale and domestic use.
- To implement a three-stage cleaning process consisting of UV sterilization, mist washing, and ozone (O_3) purification.
- To ensure effective removal of dirt, bacteria, and pesticide residues without the use of harmful chemicals.
- To reduce water and energy consumption compared to conventional fruit washing machines.
- To create a simple and user-friendly design that requires minimal maintenance and no skilled labor.
- To promote eco-friendly and sustainable technology by using safe, efficient, and reusable cleaning methods.
- To evaluate the performance and efficiency of the machine under different operating conditions..

4. SYSTEM DESCRIPTION AND METHODOLOGY

4.1 System Architecture

- **Stage 1: UV Sterilization** – Ultraviolet light is used to eliminate bacteria, viruses, and other microorganisms present on the surface of fruits.
- Wavelength Selection: UV-C light at approximately 254 nm is most effective for microbial inactivation.
- Exposure Time: Adequate exposure time is required to ensure proper sterilization, typically ranging from a few seconds to minutes depending on intensity.
- Lamp Placement: UV lamps should be positioned to provide uniform exposure across all fruit surfaces.
- Distance from Source: The intensity of UV radiation decreases with distance, so optimal spacing must be maintained.
- Fruit Movement Mechanism: Rotating or conveyor-based systems help expose all surfaces uniformly to UV light.

4.2 **Stage 2: Mist Cleaning** – A fine mist spray removes dust and surface impurities using minimal water.

- Nozzle Type: High-pressure atomizing nozzles or ultrasonic mist generators can be used to produce uniform droplets.
- Droplet Size: Smaller droplets improve surface coverage and cleaning efficiency while reducing water usage.
- Spray Pressure: Typically maintained between 2–5 bar to achieve proper atomization.
- Spray Angle and Coverage: Nozzles should be arranged to provide 360° coverage of fruits.
- Flow Rate: Controlled to ensure minimal water consumption without compromising cleaning efficiency.
- Fruit Agitation Mechanism: Rotating drum or conveyor movement ensures all surfaces are exposed to the mist.

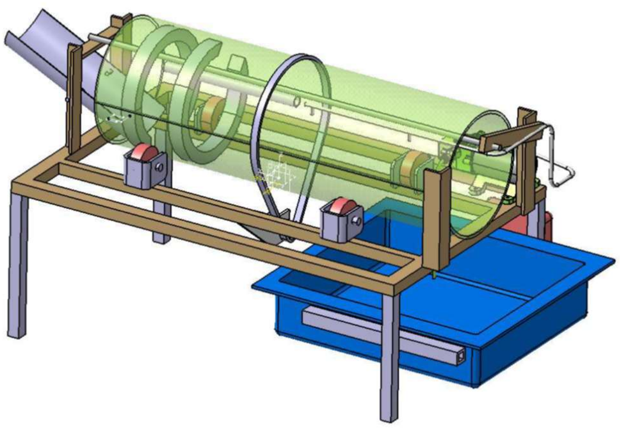
4.3 **Stage 3: Ozone Treatment** – Ozone gas (O_3) helps in breaking down pesticides, insecticides, and harmful chemical residues.

- Ozone Concentration: Typically maintained between 0.5–5 ppm depending on the type of fruit and contamination level
- Exposure Time: Adequate contact time (2–10 minutes) ensures effective degradation of chemical residues
- Generation Method: Ozone is commonly generated using corona discharge or UV-based ozone generators

- Distribution System: Uniform dispersion of ozone gas or ozonated water is necessary for consistent treatment
- Chamber Design: Enclosed chamber to prevent ozone leakage and ensure safety
- Ventilation and Decomposition: Excess ozone must be safely decomposed or vented after treatment

5. Working Principle

The proposed fruit sanitization washing machine operates on a multi-stage integrated cleaning mechanism combining ultraviolet sterilization, mist-based washing, and ozone treatment to ensure effective removal of biological and chemical contaminants.
Initially, fruits are exposed to Ultraviolet Germicidal Irradiation (UV-C radiation), which penetrates the cell walls of microorganisms and disrupts their DNA or RNA structure through the formation of thymine dimers. This prevents microbial replication and renders bacteria, viruses, and fungi inactive, thereby significantly reducing the surface microbial load without the use of chemicals.



Below is the Bill of Materials (BOM)
Sr.no Components-Qty
1. Rollers-4
2. Motor-1
3. Frame 1
4. UV LIGHT-1
5. Mist sprayer-3
6. 10-inch PVC pipe-2
7. Water tank 30 liter-1
8. Pump & O3 machine-1

Following UV treatment, the fruits undergo mist cleaning based on atomization principles. Water is converted into fine droplets (10–100 microns), forming a uniform mist that gently interacts with the fruit surface. These micro-droplets penetrate surface irregularities and effectively dislodge dust, dirt, and contaminants that were loosened during the UV sterilization stage. This process ensures thorough cleaning while minimizing water usage and preventing mechanical damage to delicate fruits.
In the final stage, fruits are subjected to Ozone oxidation using ozone (O_3). Ozone molecules decompose to release reactive oxygen species, which oxidize and break down complex pesticide and chemical residues into simpler, less harmful compounds. Simultaneously, ozone further inactivates any remaining microorganisms by disrupting their cellular structures. As ozone naturally decomposes into oxygen, the process leaves no harmful chemical residue on the fruit surface.
The integration of these three stages results in a synergistic effect, where UV sterilization reduces microbial load, mist cleaning removes physical impurities, and ozone treatment eliminates chemical residues. This combined approach ensures efficient, eco-friendly, and comprehensive fruit sanitization with minimal water and chemical usage.
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6. Design Consideration, Experimental Observations and Performance Analysis

1. Design of Chain Drive
To determine the number of teeth on the driven sprocket, the following relation is used:

$$Z_2 = \frac{Z_1 \cdot n_1}{n_2} \qquad (1)$$

Substituting the given values:

$$Z_2 = \frac{12 \times 12}{6} = 24 \text{ teeth} \qquad (2)$$

2. Design of Sprocket Diameters

The diameter of the driving sprocket is given by:

$$D_1 = \frac{P}{\sin\left(\frac{180°}{Z_1}\right)} \quad (3)$$

$$D_1 = \frac{12.7}{\sin(15°)} = 49.05 \text{ mm} \quad (4)$$

Similarly, the driven sprocket diameter is:

$$D_2 = \frac{P}{\sin\left(\frac{180°}{Z_2}\right)} \quad (5)$$

$$D_2 = \frac{12.7}{\sin(7.5°)} = 97.3 \text{ mm} \quad (6)$$

3. Determination of Centre Distance

The recommended centre distance is:

$$30P < a < 50P \quad (7)$$

Selecting:

$$a = 40P = 40 \times 12.7 = 508 \text{ mm} \quad (8)$$

The chain length in number of links is given by:

$$L_n = \frac{a}{P} + \frac{Z_1 + Z_2}{2} + \frac{(Z_2 - Z_1)^2}{4\pi^2} \cdot \frac{P}{a} \quad (9)$$

$$L_n = \frac{508}{12.7} + \frac{12 + 24}{2} + \frac{(12)^2}{4\pi^2} \cdot \frac{12.7}{508} \quad (10)$$

$$L_n = 40 + 18 + 0.09 = 58.09 \approx 58 \text{ links} \quad (11)$$

Corrected centre distance considering sag:

$$a = 0.998 \times 508 = 507 \text{ mm} \quad (12)$$

4. Chain Velocity

The velocity of the chain is given by:

$$V = \frac{Z_1 \cdot P \cdot n_1}{60 \times 1000} \quad (13)$$

$$V = \frac{12 \times 12.7 \times 12}{60000} = 0.0305 \text{ m/s} \quad (14)$$

5. Tension in Chain

The tension in the chain is given by:

$$T_1 = \frac{1000 \cdot kW}{V} \quad (15)$$

$$T_1 = \frac{1000 \times 1}{0.0305} = 32786 \text{ N} \quad (16)$$

6. Load on Shaft

$$\sin\ \alpha = \frac{D_2 - D_1}{2a} \quad (17)$$

$$\sin\ \alpha = \frac{97.3 - 49.05}{2 \times 507} = 0.0476 \quad (18)$$

$$\alpha = \sin^{-1}(0.0476) = 2.73° \quad (19)$$

Vertical component:

$$T_y = T_1 \sin\ \alpha \quad (20)$$

$$T_y = 32786 \times 0.0476 = 1560 \text{ N} \quad (21)$$

Horizontal component:

$$T_x = T_1 \cos\ \alpha \quad (22)$$

$$T_x = 32786 \times 0.9988 = 32746 \text{ N} \quad (23)$$

7. Power Transmitted by Driven Sprocket

$$V = \frac{Z_2 \cdot P \cdot n_2}{60 \times 1000} \quad (24)$$

$$V = \frac{24 \times 12.7 \times 6}{60000} = 0.0305 \text{ m/s} \quad (25)$$

$$T_2 = \frac{1000 \cdot kW}{V} = 32786 \text{ N} \quad (26)$$

Since alignment is straight:

$$\alpha = 0 \quad (27)$$

$$T_y = 0, T_x = 32786 \text{ N} \quad (28)$$

8. Resultant Tension

$$T_R = \sqrt{T_x^2 + T_y^2} \quad (29)$$

$$T_R = \sqrt{(32746)^2 + (1560)^2} = 32783 \text{ N} \quad (30)$$

9. Shaft Design

Allowable shear stress:

$$\tau_{max} = 0.18\sigma_{ut} \quad (31)$$

$$\tau_{max} = 0.18 \times 700 = 126 \text{ N/mm}^2 \quad (32)$$

Considering keyway:

$$\tau_{max} = 0.75 \times 126 = 94.5 \text{ N/mm}^2 \quad (33)$$

Torque transmitted:

$$M_t = \frac{60 \times 10^3 \cdot kW}{2\pi n_1} \quad (34)$$

$$M_t = \frac{60 \times 10^3 \times 1}{2\pi \times 12} = 795.8 \text{ N\cdotpm} \quad (35)$$

Shaft diameter:

$$d^3 = \frac{16}{\pi\tau_{max}}\sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (36)$$

$$d \approx 22\text{ mm} \quad (37)$$

Final Shaft Selection

$$d = 25\text{ mm} \quad (38)$$

Machine washing capacity
The Washing capacity was determined as follows:
C=M X 60/Tw
C=Washing capacity (Kg/hr)

M=Mass of product fed into the machine (kg)

Tw=Washing Time (min)

7. Advantages and Applications

7.1 Advantages

- Low cost and affordable for small-scale users
- Reduced water and energy consumption
- Compact and space-saving design
- Chemical-free and eco-friendly operation
- Easy to operate and maintain
- Preserves nutritional quality of fruits and vegetables

7.2 Applications

- Household fruit and vegetable cleaning
- Small-scale food processing industries
- Hotels and restaurants
- Agricultural produce handling units

8. Limitations

- UV limitation: Cannot disinfect shadowed or uneven surfaces completely.
- Ozone safety: Requires proper handling to avoid harmful exposure.
- Maintenance: UV lamps and ozone units need periodic replacement.
- Limited capacity: Not suitable for large-scale industrial use.
- Power dependency: Requires continuous electrical supply for operation.

9. CONCLUSIONS

The proposed three-stage fruit sanitization machine provides an effective, economical, and sustainable solution for improving food safety. By integrating UV, mist, and ozone technologies, the system ensures thorough cleaning while minimizing resource consumption. Its compact design and user-friendly operation make it highly suitable for domestic and small-scale industrial applications. This innovation has the potential to enhance hygiene standards and promote the adoption of eco-friendly technologies in the food processing sector.

10. Future Scope

The system can be upgraded with automation and sensors for fully automatic operation. Integration with renewable energy sources like solar power can improve sustainability. Advanced technologies such as IoT can be incorporated for remote monitoring and control. The design can be scaled up for industrial applications with higher capacity. Further improvements can be made to enhance efficiency and reduce cost for wider adoption.

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