Selection Of Optimal Parameters For Primary Processing Of Mulle Cocoons By A Combined (IR + US) Method

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Abstract

This scientific study is devoted to an experimental investigation of the effectiveness of a combined ultrasonic and infrared treatment method for reviving silkworm pupae. The study assessed the effects of treatment time, temperature, and ultrasound frequency on the degree of pupal necrosis. Experiments were conducted at a temperature of 60-80°C, an ultrasound frequency of 20-40 kHz, and a treatment time of 180-480 seconds. The results showed that the degree of necrosis consistently increased with increasing treatment time and ultrasound frequency. High efficiency was found to be achieved even at low temperatures, especially at an ultrasound frequency of 40 kHz. Based on the experimental results, optimal treatment parameters were proposed for high-quality degreasing of silkworm cocoons and minimizing the negative impact on cocoon quality. The obtained results have practical implications for the development of energy-saving and modern technological solutions in sericulture.

Keywords: Silkworm, cocoon, silk, infrared radiation, ultrasound exposure, drying kinetics, temperature, killing.

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1. Introduction

Primary processing of silkworm cocoons (killing and drying) is the most critical operation after harvesting to preserve them for further processing. Traditional hot-air processing often results in long processing times, uneven heating, and the degradation of valuable proteins such as fibroin and sericin. To overcome these limitations, hybrid technologies combining infrared (IR) radiation and ultrasound (US) have been introduced to increase the rate of heat and mass transfer. Infrared radiation provides rapid surface heating through electromagnetic energy, while ultrasound induces cavitation and microflows within the material, improving internal moisture diffusion [1].

The silkworm, which feeds on mulberry leaves, has the scientific name Bombyx mori and belongs to the Bombycidae family. The silkworm is a complete metamorphosis insect, divided into four main growth stages: egg, larva, and pupa. Moths feed only on caterpillars (Fig. 1). The silkworm's food source is mulberry leaves [2].

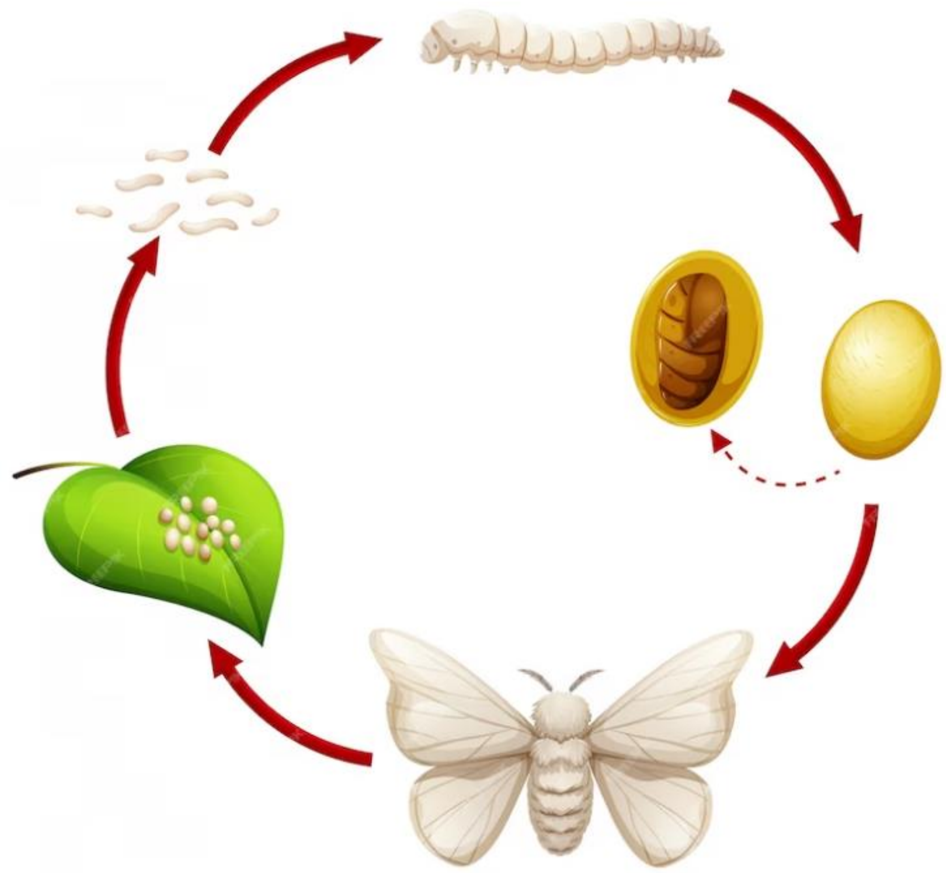

Fig. 1. Life cycle of the silkworm

In our country, silkworm farmers collect cocoons and quickly string them for primary processing to kill and dry them before the silkworm pupa turns into a butterfly and flies out of the cocoon, which makes the cocoon unusable or its quality deteriorates [3].

2. Methods

Raw Materials. New Bombyx mori cocoon samples grown in Uzbekistan were used for this study. Cocoons of uniform size, good quality, and undamaged outer shells were selected for the experiment. All samples were refrigerated for 24 hours prior to the experiment. Each drying group included 100 fresh cocoons weighing 240-250 g, with a distance of 10 cm between the cocoons and the infrared emitter [4].

Process parameters. Experimental work was conducted to effectively anesthetize silkworm pupae using a combined ultrasonic and infrared setup. Experimental testing was conducted using the following nine different combinations:

- Treatment time (s): 180, 240, 300, 360, 420, 480;

- IR wavelength (μm): 3.0;

- Ultrasound frequency (kHz): 20, 30, 40;

- Temperature (°C): 60, 70, 80;

- Infrared power: 220, 260, and 300 W.

Experimental setup. The "Processes and Equipment for Processing Agricultural and Food Products" laboratory at Tashkent State Technical University has a combined ultrasonic and infrared drying system, which was used in the research. A schematic of this device is shown in Fig. 2.

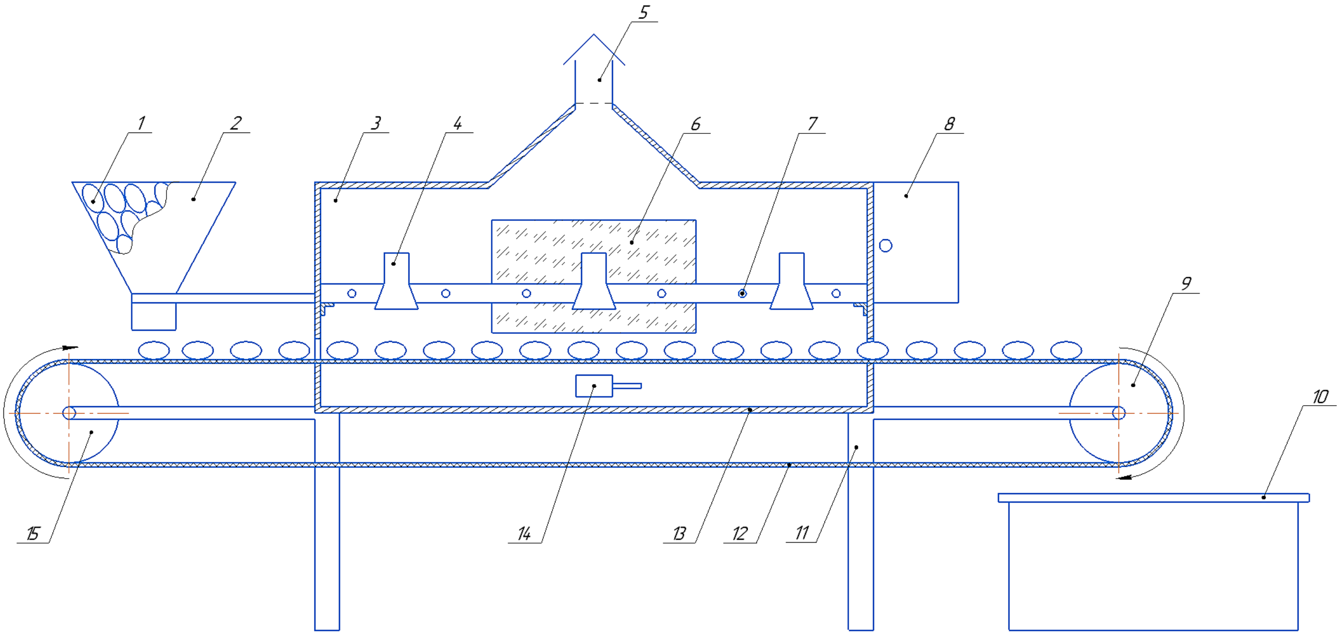

Fig. 2. Schematic diagram of the installation: 1 - fresh cocoon harvest; 2 - cocoon loading bin; 3 - working chamber; 4 - ultrasonic emitters; 5 - ventilation system with a fan for removing moisture; 6 - process observation window; 7 - ceramic infrared emitters; 8 - control unit; 9 - driven shaft of belt conveyor; 10 - cocoon collection container; 11 - device legs; 12 belt conveyor; 13 - infrared reflectors; 14 - thermocouple; 15 - drive shaft of belt conveyor.

Processing method. Freshly harvested cocoons 1 are placed in loading hopper 2. Control unit 8 activates the unit's infrared emitters. The cocoons are then loaded onto belt conveyor 12 and heated to the set temperature. Once the drying temperature is reached, the conveyor starts, and the cocoons are fed into working chamber 3 for pre-treatment. Control unit 8 activates the ultrasonic generator. The belt conveyor speed is regulated by control unit 8. Infrared reflectors direct the beams throughout the chamber onto the raw material. The chamber temperature is controlled by thermocouples 14. The ultrasonic emitters used in the unit periodically impact the raw material, with an interval of 10 seconds between each impact. Infrared radiation transfers heat directly to the material, accelerating moisture evaporation, while ultrasonic waves promote uniform heat distribution and increase the rate of moisture evaporation. The combination of these two methods enables efficient degreasing and drying, as well as a significant reduction in energy consumption.

This unit is designed for killing and drying silkworm pupae. One of the advantages of this unit is the ability to combine infrared radiation with ultrasonic waves, allowing for the selection of processing parameters within the required ranges. Simultaneous thermoradiation and mechanoacoustic effects are possible by simultaneously applying infrared (IR) and ultrasonic (US) waves to the treated object.

3. Results And Discussion

The results obtained in the experimental trials on killing silkworm pupae are presented in detail in Tables 1-9 below.

According to Table 1, with increasing processing time at a temperature of 60°C and an ultrasonic frequency of 20 kHz, the pupae mortality rate consistently increased. While mortality after 180 seconds was 85.1%, after 300 seconds, this figure reached 92.9%. In the range of 360-420 seconds, the mortality rate was approximately 95-97%, with almost complete mortality (99.7%) achieved after 480 seconds. This demonstrates that at low temperatures and relatively low frequencies, process efficiency is primarily determined by time.

Table 1

Results of an experiment on killing silkworm pupae with 20 kHz ultrasound at 60 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	20	60	220	85,145
240	3	20	60	220	88,194
300	3	20	60	220	92,852
360	3	20	60	220	95,531
420	3	20	60	220	97,608
480	3	20	60	220	99,721

At an ultrasonic frequency of 20 kHz and a temperature of 70°C, the death process occurred more rapidly than at 60°C. After just 240 seconds, mortality exceeded 92%, and after 300 seconds, it was 95.9%. Complete (100%) anesthesia was achieved in 480 seconds. Thus, increasing the temperature resulted in increased thermal and acoustic effects on the pupa tissue, which reduced the processing time.

Table 2

Results of an experiment on killing silkworm pupae with 20 kHz ultrasound at 70 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	20	70	220	87,954
240	3	20	70	220	91,996
300	3	20	70	220	95,924
360	3	20	70	220	97,901
420	3	20	70	220	98,135
480	3	20	70	220	100

At an ultrasonic frequency of 20 kHz and a temperature of 80°C, the necrosis process was more intense. Within 300 seconds, the mortality rate reached 96.9%, and within 420 seconds, complete mortality was achieved. However, high temperatures increase the likelihood of negative impacts on the cocoon shell and silk quality. Therefore, although this mode is technologically effective, there are limitations in terms of quality.

Table 3

Results of an experiment on killing silkworm pupae with 20 kHz ultrasound at 80 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	20	80	220	88,912
240	3	20	80	220	91,975

300	3	20	80	220	96,942
360	3	20	80	220	98,923
420	3	20	80	220	100
480	3	20	80	220	100

Increasing the ultrasound frequency to 30 kHz significantly increased anesthesia effectiveness. After 300 seconds, the resuscitation rate was 97.5%, and after 420 seconds, the result was virtually complete. This confirms that increasing the ultrasound frequency enhances the effects of cavitation and mechanical vibrations, leading to a more rapid decline in pupa viability.

Table 4

Results of an experiment on killing silkworm pupae with 30 kHz ultrasound at 60 °C

Processing time (seconds)	IR wavelength (μm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	30	60	260	89,989
240	3	30	60	260	92,627
300	3	30	60	260	97,531
360	3	30	60	260	98,839
420	3	30	60	260	99,945
480	3	30	60	260	100

The combination of 70°C and 30 kHz proved to be one of the most effective modes. Mortality was approximately 9% after 180 seconds, and complete mortality was achieved in just 300 seconds. This mode is time-saving and highly effective.

Table 5

Results of an experiment on killing silkworm pupae with 30 kHz ultrasound at 70 °C

Processing time (seconds)	IR wavelength (μm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	30	70	260	95,991
240	3	30	70	260	98,976
300	3	30	70	260	99,891
360	3	30	70	260	100
420	3	30	70	260	100
480	3	30	70	260	100

At a temperature of 80°C and a frequency of 30 kHz, the killing process was very rapid. After just 240 seconds, the mortality rate approached 99%, and after 300 seconds, 100% was recorded. However, due to the potential negative impact of high temperatures, this mode should be used with caution in industrial settings.

Table 6

Results of an experiment on killing silkworm pupae with 30 kHz ultrasound at 80 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	30	80	260	96,851
240	3	30	80	260	98,982
300	3	30	80	260	100
360	3	30	80	260	100
420	3	30	80	260	100
480	3	30	80	260	100

At an ultrasonic frequency of 40 kHz, the necrosis process was highly effective even at a temperature of 60°C. The kill rate was 98.9% after 300 seconds, and complete kill was achieved after 420 seconds. This combination is particularly important, as it enables high results at low temperatures.

Table 7

Results of an experiment on killing silkworm pupae with 40 kHz ultrasound at 60 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	40	60	300	98,145
240	3	40	60	300	99,194
300	3	40	60	300	100
360	3	40	60	300	100
420	3	40	60	300	100
480	3	40	60	300	100

At a temperature of 70°C and a frequency of 40 kHz, mortality reached 99.9% in just 300 seconds. Full anesthesia was achieved in 420 seconds. This mode is highly effective, relatively fast, and maintains quality.

Table 8

Results of an experiment on killing silkworm pupae with 40 kHz ultrasound at 70 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	40	70	300	96,954
240	3	40	70	300	98,996
300	3	40	70	300	99,963
360	3	40	70	300	99,923
420	3	40	70	300	100

480	3	40	70	300	100

At maximum temperature and frequency, the killing process reached its maximum speed. In the 240-300 second range, mortality exceeded 99.9%. However, since high temperatures can degrade cocoon quality, this mode is primarily suitable for short-term processing.

Table 9

Results of an experiment on killing silkworm pupae with 40 kHz ultrasound at 80 °C

Processing time (seconds)	IR wavelength (µm)	Ultrasound frequency (kHz)	Temperature (°C)	Infrared radiation power (W)	Degree of inactivation of pupae (%)
180	3	40	80	300	97,944
240	3	40	80	300	99,932
300	3	40	80	300	99,947
360	3	40	80	300	100
420	3	40	80	300	100
480	3	40	80	300	100

Experimental results showed that ultrasonic frequency and temperature are the main factors influencing the process of silkworm pupae resuscitation. As frequency increases, the degree of necrosis increases sharply, while processing time is significantly reduced. However, excessive temperature increases can negatively impact cocoon quality [5, 6].

4. Conclusions

The experiment showed that the optimal combination was a processing time of 300 seconds, an IR wavelength of 3.0 µm, an ultrasound frequency of 40 kHz, a power of 300 W, and a temperature of 60°C. This regime, while ensuring a high level of necrosis, maximizes the quality of cocoons and raw silk.

A series of experiments were conducted on the pre-treatment of silkworm pupae using a combined ultrasound and infrared device. Based on the experiment's results, the following combination was selected as the optimal parameters: processing time of 300 seconds, an IR wavelength of 3.0 µm, an ultrasound frequency of 40 kHz, and an ultrasound power of 300 W. This combination ensures high-quality degreasing of silkworm pupae while maximizing the quality of the cocoon.

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