INNOVATIVE TECHNICAL SYSTEMS USED IN SERICULTURE – A REVIEW
/
SISTEME TEHNICE INOVATIVE UTILIZATE IN SERICICULTURA – A REVIEW

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ABSTRACT
Silk is a biomaterial with remarkable properties, used in various fields: the textile industry, aeronautics, medicine, etc. Sericulture is the practice of raising silkworms to obtain silk threads. This activity provides an opportunity to improve economic and social status, especially for rural populations. The high demand for labor, along with technical progress, has led to the necessity to implement technical solutions and modern activities in sericulture farms. This paper presents a brief analysis of the current state of research on some innovative technical solutions applied in sericulture sectors and activities, aimed at increasing silk thread production.

REZUMAT
Mătasea este un biomaterial cu proprietăți deosebite, utilizat în diverse domenii: industria textilă, aeronautică, în medicina, etc. Sericicultura se ocupa cu creșterea viermilor de mătase pentru obținerea firelor. Aceasta activitate oferă posibilitatea de creștere a statutului economic si social, mai ales pentru populația rurala. Consumul ridicat de forță de muncă, precum si progresul tehnic au impus implementarea unor soluții tehnice și activități moderne în fermele sericicole. Aceasta lucrare prezintă o scurtă analiză a stadiului actual al cercetărilor privind unele soluții tehnice inovative aplicate in sectoarele și activitățile din sericicultură, în vederea sporirii producției de fire de mătase.

INTRODUCTION
Sericulture is a science (a branch of zootechnics) that focuses on the breeding and multiplication of silkworms for the purpose of obtaining cocoons intended for processing. In 2022, UNESCO inscribed "Sericulture and traditional production of silk for weaving" (17.COM) on the Representative List of the Intangible Cultural Heritage of Humanity *(https://ich.unesco.org/en/RL/sericulture-and-traditional-production-of-silk-for-weaving-01890#video).*

According to the ISC *(International Sericultural Commission)* statistics for 2022, the total silk production was 91,319 metric tons, produced by 22 countries, with 8 of them being the main producers, accounting for 99.9% of the total production. China, which holds the lead, contributed over half of the world's production (approximately 55%), followed by India, which provided 40%. 90% of the silk was obtained from the mulberry silkworm, while the remaining 10% was non-mulberry silk, produced by silkworm species that feed on plants other than mulberry *(https://inserco.org/en/statistics).* These species include: *Antheraea mylitta, Antheraea assamensis,* and *Samia ricini,* producing types of silk such as Tasar, Eri, and Muga. Only India produces all these commercial types of silk, which are also classified based on the number of generations of silkworms in a year: univoltine, bivoltine, and multivoltine *(Taufique and Hoque, 2021; Gautam et al., 2022; Kaviraj et al., 2021).* The mulberry silkworm *(Bombyx mori* L.*),* a moth in the order Lepidoptera, is monophagous and survives only on mulberry leaves. It is the only domesticated insect since ancient times, in China between 2600 and 2700 BC, for silk fiber production. The finest silk, known as "The Queen of Textiles," is obtained from it, characterized by its glossy shine, softness, elegance, and durability *(El-Shewy and Elgizawy, 2017; Hailu, 2016).* Silk threads are known for their extraordinary biocompatibility with the human body, along with a range of exceptional properties: elasticity, high strength, and hardness. Additionally, these animal-origin threads are eco-friendly and biodegradable compared to synthetic fibers, which are polluting *(Popescu et al., 2024; Baci et al., 2021).* They are produced by the silk glands of mature larvae in the fifth stage. They are a natural polymer of silk proteins, consisting of fibroin and sericin, produced in PSG (posterior silk gland) and, respectively, MSG (middle silk gland). Fibroins are the basic fibrous proteins and are hydrophobic, while sericins surround the fibroins and are hydrophilic. The anterior silk gland (ASG) is the third division of the silk gland in silkworms, where the liquid silk protein is assembled into silk fibers *(Saikia and Saikia, 2022; Zhu et al., 2022).*

Sericulture has the advantage of being practiced profitably both on a small, artisanal scale and on an industrial scale, capable of scalable production *(Altman and Farrell, 2022).* This rural and ecological industry comprises three interconnected sectors: sericulture, which deals with the cultivation of mulberry *(Morus sp.)* to provide food for the silkworms *(Bombyx mori),* which form the protective cocoon, from which raw silk threads are obtained through various processes in the post-cocoon sector *(Chanotra and Bali, 2019).* The goal is to produce high-quality cocoons with the highest silk content, with current efforts focusing on the most efficient use of this precious material. Beyond traditional uses related to fashion (clothing, shoes, bags, wallpapers, etc.), technological progress has made silk indispensable for medicine, nanotechnology, biotechnology, optical industry, etc. The entire activity of producing primary products represented by natural fibers generates various by-products and waste, which are aimed to be utilized as efficiently as possible *(Reizabal et al., 2023; Hăbeanu et al., 2023; Lujerdean et al., 2022; Jaiswa et al., 2021; Pop et al., 2018).* The use of by-products (such as silkworm pupae) for animal feed, food, cosmetics, vermiculture, biogas production, artisanal products, etc., by promoting circular economy supply chains, represents new trends in sericulture. Additionally, all these applications and activities reduce environmental impact, increase employment in certain rural areas, and raise their socio-economic level *(Seo et al., 2023; Ekka and Bais, 2023; Tassoni et al., 2022; Sharma et al., 2022; Barcelos et al., 2021).*

Since sericulture involves multiple sectors and activities, mechanization in sericulture refers to: agricultural tools, machines, and equipment for mulberry cultivation (land preparation, crop maintenance), harvesting mulberry leaves and proper storage, systems for silkworm rearing, and machinery for the post-cocoon sector. Machinery is important for increasing land and labor productivity, helping manage activities that must be performed within specific time frames. It is also indispensable for the actual production of silk fabrics, with the quantity and quality of the silk depending on it *(Karthick Mani Bharathi et al., 2024; da Silva et al., 2018).*

Silkworms are very sensitive to their diet, specifically the quantity and quality of the food, as well as to environmental factors such as temperature, humidity, light, and air. Silkworm rearing is strongly influenced by the rearing techniques adopted, including feeding, cleaning, spacing, etc. An unsuitable environment negatively impacts the growth of silkworms, and consequently, the quantity and quality of the cocoons *(Gupta and Dubey, 2021; Andadari et al., 2021).* Immediately after collection, silkworm cocoons undergo several operations. They are steamed/dried (to destroy the butterfly pupa) after being pre-sorted, with undeveloped or double cocoons removed. The goal is to preserve their quality for long-term storage. Properly conditioned cocoons can undergo further operations to obtain silk threads: final sorting, cleaning of impurities, scalding, reeling, etc. A wide range of machinery has been studied and optimized for these operations *(Safarov et al., 2019; Angel et al., 2018; Alim et al., 2016).*

It is important for improved silkworm rearing technologies to be known and adopted by farmers in the field. Enhancing competence in sericulture depends on investment, promotion of technologies, and advancements in professional training. Modern agricultural technologies and production systems have the potential to increase efficiency and open new opportunities for various agricultural methods *(Vlăduț and Ungureanu, 2024; Hajam et al., 2021; Singh et al., 2021).*

The paper provides a brief overview of the current state of research on innovative technical solutions applied to mulberry shoot cutting, monitoring/control of silkworm growth factors, and the post-cocoon sector, aiming to reduce labor and energy consumption, thereby improving the efficiency of operations and the final quality of silk.

MATERIALS AND METHODS

The quality and nutritional composition of mulberry leaves influence the growth performance of silkworms *(Gheorghe et al., 2023).* In sericulture, obtaining these leaves is a major issue. Mulberry branches are cut individually, which requires significant time and labor. Cutting can be done with a hydraulic shear or other cutting tools/machines. Therefore, research has been conducted to reduce the physical effort exerted by the operator. A device was developed for this operation, featuring a mobile arm and a rotating saw (fig. 1). The cut branches are collected in a tray specifically designed for this purpose. Figure 2 shows the block diagram of the device's operation *(Kumar et al., 2021).*

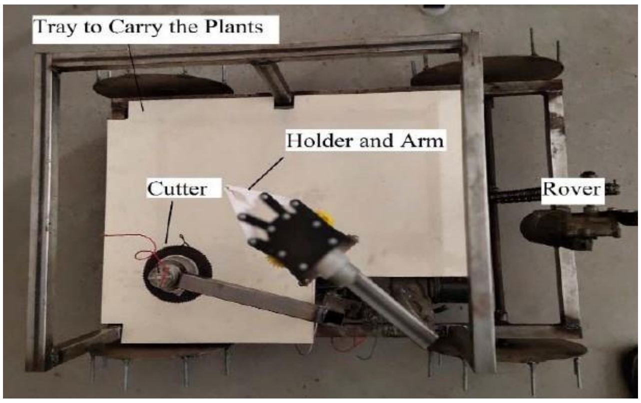

Fig.1 - Mulberry Branch Cutting Device
(Kumar et al., 2021)

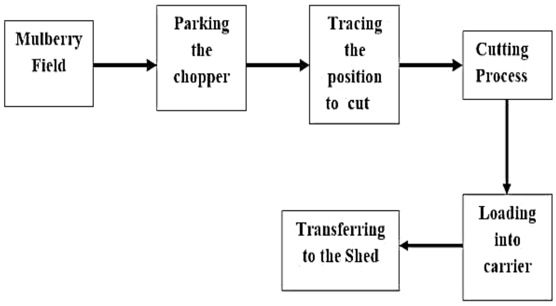

Fig.2 - Block diagram
(Kumar et al., 2021)

The arm is attached to a rod driven by a DC motor (like those used in windshield wipers), allowing the arm to move in the desired direction, meaning its opening and closing are controlled. The circular saw is also powered by a DC motor, but with high torque for effective cutting. The cutting device is manually moved to the position of the branch that needs to be cut. The automatic module is activated, and the control system manages and monitors the sequence of operations:

- The support holding the arm opens so that the arm can extend outward to grasp the branch, then it closes.
- The open-source Arduino Uno platform immediately activates the cutting system, and the arm extends to cut the branch.
- After cutting, the arm holding the mulberry branch retracts, loosening its grip. This sequence is controlled by the controller and relay.
- Finally, the branch is discharged into the storage tray, and the cycle repeats *(Kumar et al., 2021).*

In China, several research efforts have focused on developing mulberry leaf harvesting equipment, including piston-type, spiral-type, semi-automatic, and multi-degree-of-freedom devices. However, these innovations have not eliminated manual labor, although they have reduced the physical effort required by operators and improved the efficiency of the picking operation. As a result, research has been initiated to develop intelligent mulberry leaf harvesting techniques. The first stage involves locating the picking points. Using appropriate infrastructure, researchers began by identifying and segmenting the harvesting nodes area through the development of a Mask R-CNN model, which classifies nodes based on their shape ("Y" or "rectangle"). This model was then optimized to enhance recognition accuracy. Finally, a method was devised to obtain the picking points of the mulberry leaf nodes, along with visual information for intelligent harvesting *(Zeng et al., 2023).* Mask R-CNN is a Convolutional Neural Network (CNN) and represents the state-of-the-art in image segmentation. This Deep Neural Network variant detects objects in an image and generates high-quality segmentation masks for each instance. Researchers developed Mask R-CNN based on the original Faster R-CNN, a Region-Based Convolutional Neural Network, by extending it with an additional branch and using existing detection to predict the target in parallel *(Hassan et al., 2022).*

Other researchers have used neural networks to develop early detection models for mulberry leaf diseases, aiming to combat these diseases and prevent the use of affected leaves as feed for silkworms, as they negatively impact their health and development (*Nahiduzzaman et al., 2023).*

In agriculture, robots are often mobile platforms, which have seen remarkable development over the past decade *(Shamshiri et al., 2018).* Research has been conducted to expand their use in sericulture, particularly for handling large frames used in the rearing process of silkworms. For a stacking device, a model of a mobile transport platform was designed (fig. 3), focusing on making it: compact, capable of movement along two axes, with reduced construction and functional complexity, thus resulting in a low production cost while still achieving high efficiency in handling and placing the frames. The mobile platform (fig. 3) includes: (1) electric drive motors, (2) rack-and-pinion transmission for movement along the X axis (horizontal), (3) rack-and-pinion transmission for movement along the Z axis (vertical), (4) frame gripping system for silkworm frames (not described in this work). Additionally, (5) the main frame of the device supports the mobile transport platform. For movement along the X axis, the pinion of the rack-and-pinion transmission receives motion from the electric motor via a straight-toothed gear mounted on its shaft, forming a cylindrical gear system.

The pinion shaft is supported by two sliding bearings located on either side. The bearings are mounted on the mobile platform, which slides. Thus, Figure 4 shows: (1) the mobile platform, (2) the cylindrical gear system, (3) the rack, (4) the guide, (5) the pinion shaft for the rack-and-pinion transmission, (6) the roller bearings. For movement along the Z axis, the pinion of the rack-and-pinion transmission receives motion from the electric motor via a bevel gear system (fig. 5). On the shaft of the electric motor (5), a bevel pinion engages with the bevel gears (4) which transmit motion to the pinion (2) through a common shaft supported by bearings (3) mounted on the mobile platform (1). The pinion (2) moves along the rack (6) *(Jiang et al. 2024).*

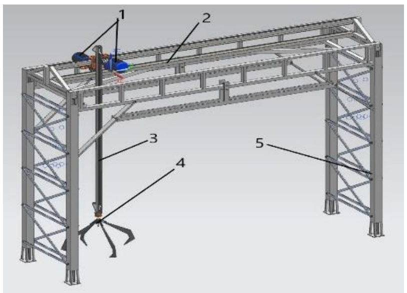

Fig.3 - Mobile Transport Platform *(Jiang et al., 2024)*

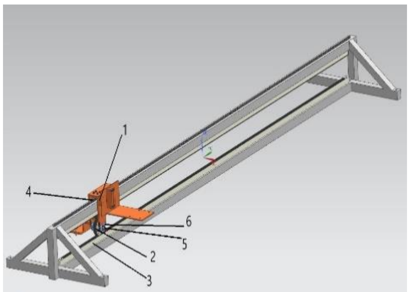

Fig.4 - Movement Transmission of the Mobile Platform along the X Axis *(Jiang et al., 2024)*

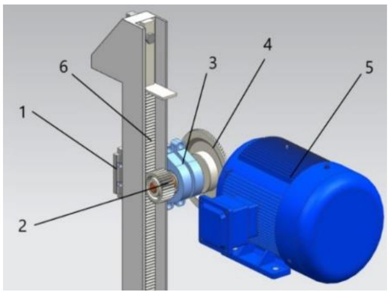

Fig.5 - Movement Transmission of the Mobile Platform along the Z Axis *(Jiang et al. 2024)*

Considering the dimensions of the frames (1000mm x 1500mm), the stacking height of these frames in a group (2000 mm), the distance between the platform and the frame gripping system (500 mm), as well as the horizontal distances that need to be maneuvered, the height of the main frame was established as 3000 mm, and the length of the transverse beam as 4000 mm. For the pinion shafts of the rack-and-pinion transmissions, made of quality carbon steel (with 0.45% C content), a strength check was conducted using simulated modal analysis *(Jiang et al., 2024).*

To avoid losses in sericulture, in addition to diet, monitoring environmental factors and the health status of silkworms is critically important *(Bekkamov and Samatova, 2023; Chopade et al., 2021*). Numerous research efforts have been undertaken, resulting in various automated systems or methods (experimental or prototypes) designed to be as efficient, cost-effective, and interactive for farmers as possible. Although these systems aim for the same goal, they differ in their components and technologies used.

Thus, a system was developed that utilizes a microcontroller combined with a GSM module to offer tracking and automatic control features. The automated system, with the architecture shown in Figure 6, detects temperature, light intensity, humidity, and gases (LPG, carbon dioxide) in the sericulture farm environment. These represent the inputs, and when threshold values are exceeded, information is transmitted to the user via a wireless network, with the microcontroller taking necessary actions (e.g., correcting temperature, humidity, air quality, light intensity, etc.) to avoid losses due to silkworm deaths. The system communicates with the user via the GSM module to perform tasks such as feeding the silkworms. The system can be divided into: a detection part and an action part *(Gunasheela et al., 2018*).

In another study, a similar embedded system was developed (fig.7) for close monitoring and regular control of environmental parameters in the silkworm rearing chamber/enclosure. The system maintains temperature, humidity, light intensity, and CO2 concentration. It is equipped with a fire alarm, and also ensures the distribution of food and medicine for the silkworms.

The system consists of sensors, an Arduino controller, and actuators (cooling fan, food dispenser, medication sprayer). The sensors circuit comprises four analog sensors: temperature, humidity, light, and CO2 sensors, and a digital fire sensor. The Arduino is programmed with threshold values and the capacity to monitor and control the system. The system comprises both software and hardware components *(Manjunatha and Neelagar, 2018).*

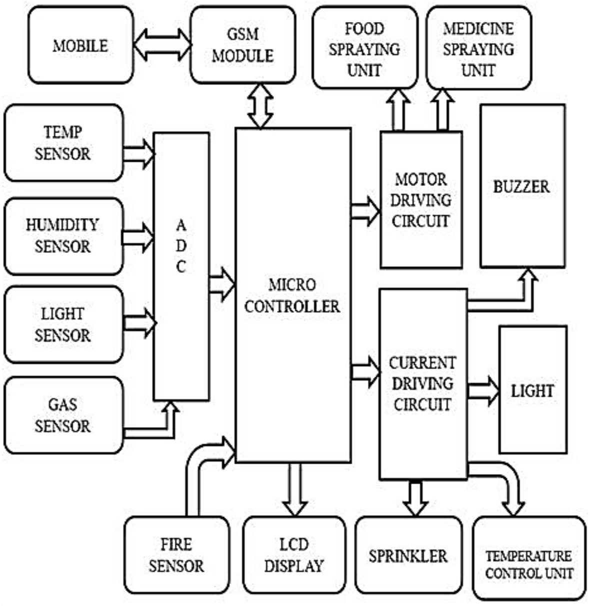

Fig.6 - Architecture of the Automated System
(Gunasheela et al., 2018)

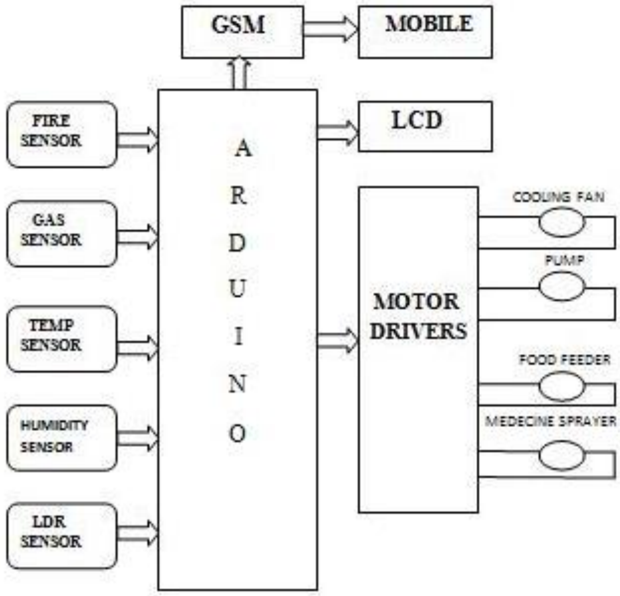

Fig.7 - Embedded System Diagram
(Manjunatha and Neelagar, 2018)

For a silkworm incubator (fig.8), a monitoring system was used that employs an open-source, low-cost data acquisition and transmission system. This system utilized an embedded platform with cloud remote monitoring through the Google Drive file hosting service and the Internet of Things. The proposed conceptual model (fig.9) includes: sensor readings, communication channel, and data storage in the cloud. Several sensors record environmental parameters (humidity, temperature, and light) in a silkworm incubator. The information is uploaded to the Google Drive cloud via Wi-Fi. With a username and password, information can be accessed from any device that can access Google Drive. The system is highly flexible, with possibilities for expansion or adaptation. The monitoring system was used in the silkworm incubator (*Incubapremium Columbia type*) equipped with 9 trays with metal mesh (food-grade aluminum) to allow air circulation, for 200 silkworms, continuously for 25 days. The trays for silkworms (1x0.6m) are arranged on shelves, spaced 15 cm apart. *(Duque-Torres et al., 2018).*

Fig.8 - Silkworm incubator
(Duque-Torres et al., 2018)

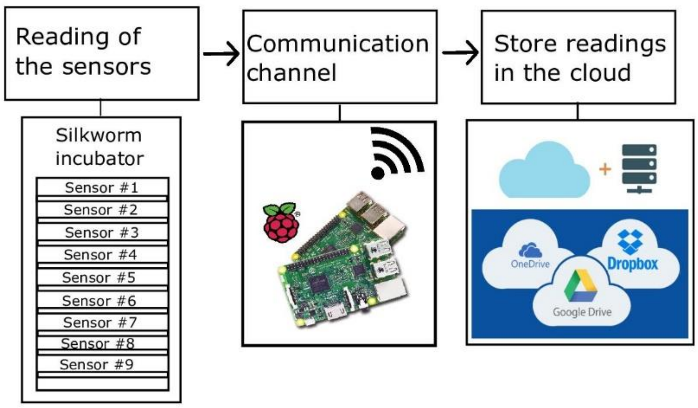

Fig.9 - Silkworm incubator monitoring system conceptual model *(Duque-Torres et al., 2018)*

The temperature in the chamber is controlled by a heating system based on an electric heater, and a humidifier placed in the lower part of the incubator controls the humidity. For monitoring, DTH22 sensors were used. Silkworms are photosensitive and do not like light that is too strong or too weak. For light measurement, the APDS-9301 sensor was used due to its high accuracy and low energy consumption. For the prototype of the monitoring system, a Raspberry Pi version 3 (RPi3) controller was used due to its technical and economic advantages *(Duque-Torres et al., 2018).*

In another study, an advanced monitoring and control system for ecological conditions in a silkworm incubator was proposed (fig.10), based on the use of an Arduino Uno microcontroller due to its numerous capabilities. To ensure favorable conditions for silkworm development in the incubator, temperature and humidity are the primary factors to be controlled. Their estimation is done continuously. The threshold levels for temperature and humidity can be easily set and modified remotely from a portable device. When the temperature falls below the set value, the microcontroller is programmed to activate the heater loop. When the humidity falls below the threshold value, the humidifier is activated. Temperature and humidity can be checked remotely *(Kokila et al., 2021).*

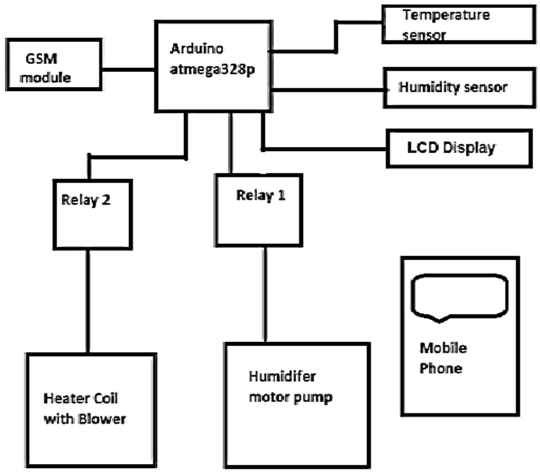

Fig.10 - Block diagram of advance silkworm incubator with environment control
(Kokila et al. 2021)

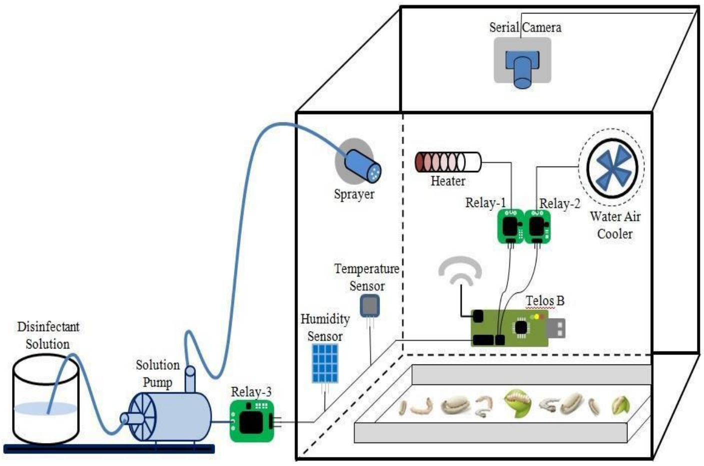

Fig.11 - IoT based Block Representation of the Sericulture Monitoring and Actuation System
(Arun et al., 2019)

To prevent unfavorable conditions and actions affecting the development of silkworms (such as temperature variation, humidity, lack of food, disease occurrence, etc.), an Automated Smart Sericulture System has been developed. Figure 11 shows the proposed system architecture for a silkworm rearing chamber, based on IoT, consisting of temperature and humidity sensors, a camera, actuating devices (electric heater, cooler, digital image processing, sprayer) connected to smart nodes, with wireless communication. Based on real-time data provided by the sensors, the smart nodes will make decisions and perform actions. Raw images from the camera are digitally processed to extract improved versions and additional information. For visualization, application development (using various built-in signal processing algorithms), and numerical calculations, MATLAB will be used *(Arun et al., 2019).*

In another study, for classifying silkworms as healthy or unhealthy, CNN neural network archives were used due to their proven high accuracy for less complex elements. The proposed system consists of two parts: Hardware and Software. For these, widely available component parts, open-source software such as Arduino IDE and Rest API, and commercial software MATLAB for image processing techniques were utilized *(Yogeshraj et al., 2022)*.

Regarding post-cocoon operations, two methods (infrared drying and combined drying) were investigated and compared for their effectiveness in killing and drying silkworm cocoons. Fresh cocoons stored in the refrigerator were maintained at room temperature for 15 minutes before drying. The cocoons were spread out in a single layer on stainless steel trays of the drying equipment used. The entire sample was weighed every 30 minutes to trace the drying curves. An infrared laboratory dryer of type "ASIA," with a power of 750 W, incorporating three 250 W infrared emitters, and an experimental dryer with a 50 Hz ultrasonic frequency and 1000 W IR radiation power were used. Drying temperatures for both experiments were set at 60°C, 65°C, and 70°C, with an ultrasonic exposure time of 10 seconds. Initial material moisture, instantaneous moisture, and drying rate for a specific time interval Δ*t* were calculated. Experimental data were processed using statistical analysis programs *(Samandarov et al., 2023).*

During the life cycle of silkworms, gender classification of cocoons is important for ensuring the perpetuation and preservation of genetic material through egg production, as well as for post-cocoon operations. A non-destructive multi-sensor system for gender classification and separation of silkworm cocoons was developed, with the schematic and prototype shown in Figures 12 and 13.

The machine consists of the vertical conveyor module (VCM) that individually picks up cocoons from the hopper at a constant speed without causing physical damage, and then transfers them to the feature extraction module (FEM). Here, each cocoon is analyzed, extracting data related to its shape and weight. Using dedicated software running on an autonomous workstation, a digital image is obtained. The image characteristics and weight information are combined into an input feature vector, analyzed by a pre-trained pattern recognition classifier for making decisions regarding gender classification/sorting. The final module is a horizontal conveyor (HCM) that directs individual cocoons to be physically sorted and blown into designated baskets (male or female) *(Raj et al., 2019).*

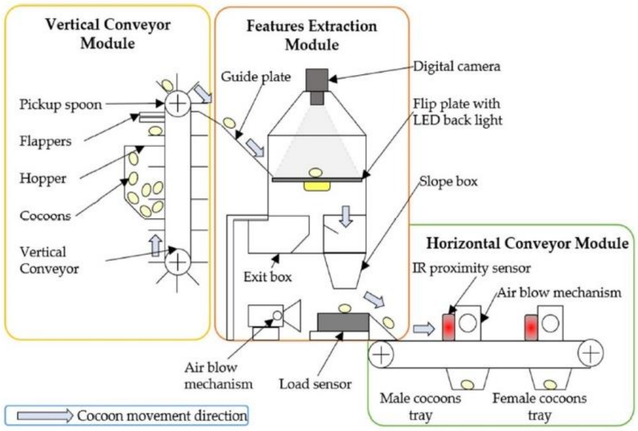

Fig. 12 - The scheme of the machine for separating cocoons by gender *(Raj et al. 2019)*

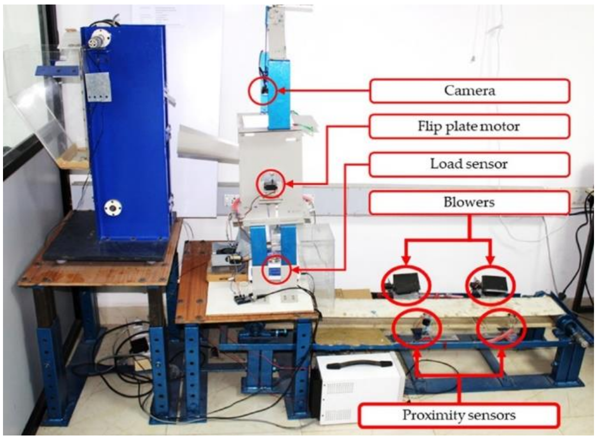

Fig.13 - The prototype of the machine for separating cocoons by gender *(Raj et al., 2019)*

VCM is a vertical belt conveyor driven by an electric motor (12V, 10 rpm). On the belt, which has a speed of 6.3 cm/s, 16 special, concave pockets shaped like spoons are mounted equidistantly by riveting. Two rows of flaps help remove excesses, so each pocket only holds one cocoon. FEM consists of a support frame with a mount for a 5-megapixel digital camera, an inclined feed chute, an output chute, a detachable load sensor, and a blowing system. Image processing and cocoon weight measurement provide information sent to a binary classifier to determine gender. Under the camera, there is a tilting acrylic plate that, through a shaft driven by a servomotor, can be positioned in three directions (horizontal 0°, 90° clockwise, -90° counterclockwise). The tilting plate receives cocoons from the VCM in the horizontal position. A square LED panel light (18 W), directed from back to front, is used to capture the hard shell silhouette of the cocoon, allowing precise area calculation through image threshold techniques. The cocoon is transferred to the load sensor after the image is acquired. The falling speed of the cocoon is dampened by moving across multiple inclined planes. Cocoon weight data is acquired with an error of 0.01 g and transferred to the workstation after reaching the load sensor surface. The cocoon is transferred to the HCM using a blowing system, which consists of a blower and a pivoting “U” shaped cover that stops the air flow. One side of the cover is coupled to a servomotor, while the other rotates freely relative to the wall via a cylindrical pin joint. Normally, the cover is closed, and no airflow is directed towards the cocoon. Once weight data is acquired, the system sends a command to the servomotor, and the pivoting arm opens for 2 seconds to allow cocoon transfer. The power requirement for FEM is 25 W. HCM consists of a horizontal belt conveyor, 2 infrared proximity sensors (IR) paired with 2 blowing units, all placed along the conveyor. The positions were empirically determined to ensure the workstation has the necessary time for classification index calculation and provision. Based on this, the blowers in each pair are activated/deactivated to transfer the cocoon to the appropriate tray *(Raj et al., 2019).*

The quality and lighting of the image were aimed to be optimized to obtain the best experimental conditions, so the Otsu Method was used for processing. Thus, this algorithm performs thresholding for image binarization on the acquired image. In the FEM module, an image is obtained and sent to the workstation, where shape characteristics (area, perimeter, major axis length, minor axis length, etc.) are calculated. The area of the cocoon from the binarized image is compared with an empirical threshold value. If the threshold is exceeded, excess cocoons are ejected by rotating the tilting plate counterclockwise, moving them out of the module through the output box to return to the feed hopper. If only one cocoon is on the tilting plate, the binarized image area does not exceed the threshold.

The microcontroller is signaled to rotate the tilting plate clockwise, and the cocoon reaches the load sensor, where its weight is acquired and transmitted to the workstation.

Shape and weight characteristics are combined and sent to a pre-trained SVM (Support Vector Machine), assigning an index and gender label stored in the workstation. The air blowing system moves the cocoon from the sensor to the HCM. As it moves, the cocoon reaches the first proximity sensor (IR), which sends a signal to another microcontroller. This retrieves the classification label of the current cocoon to control the blowers. If the designated label is “male,” the first blower is activated, pushing the cocoon onto the “male cocoon tray.” Conversely, if the cocoon's label is “female,” the second blower is activated, pushing the cocoon onto the “female cocoon tray.” The prototype of the machine for separating cocoons by gender was tested on two silkworm races, CSR2 and Pure Mysore, provided by an industry partner *(Raj et al., 2019).*

Additionally, to further optimize the sorting operation, which can be done before drying cocoons and before spinning, a prototype was developed based on a patent No. IT201900016208A1. Unlike the previously mentioned equipment that uses one camera and several sensors, this one relies on three cameras and image algorithms that identify the shape, size, and external spots of cocoons, along with a custom light sensor and an AI model to remove dead cocoons. The equipment (Fig. 14), which practically embodies a patented invention, is an opto-electrical machine, with cocoon selection occurring through three zones, each with different functions *(Vasta et al., 2023, Assirelli et al., 2019*).

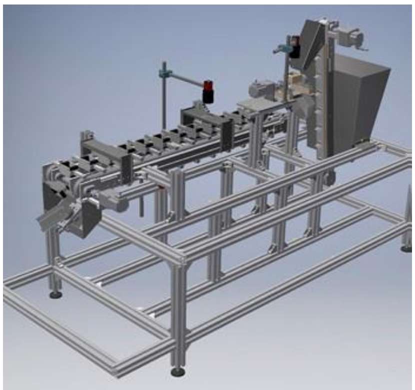

Fig. 14 - 3D CAD render of the prototype *(Vasta et al., 2023)*

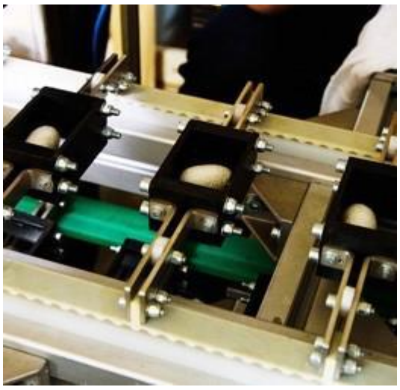

Fig. 15 - Custom-made conveyor belt *(Vasta et al., 2023)*

Fig.16 - Screenshot of GUI written in Java *(Vasta et al., 2023)*

The equipment was built around a conveyor belt (Fig. 15) driven by a stepper motor, with all mechanical movement systems controlled by a programmable PLC. It also controls the solenoid valves that activate the pneumatic actuators for initial and final selection (Fig. 16). The frame of the equipment was made from aluminum profiles, and the horizontal conveyor, having a special construction, was custom-made. The feeding is done with a vertical feeding system that directs the cocoons to an inclined feeding chute at 45° (Fig. 14). The first camera was placed at the end of this chute, and the two pneumatic actuators, mounted perpendicular to its direction, serve to remove cocoons that are unsuitable in shape. Those approved in shape fall into small capsules placed on the horizontal conveyor. Due to the horizontal movement of the belt, each capsule with a cocoon inside reaches the next two specialized cameras for spot selection, one providing an image from bottom to top and the other from top to bottom. This way, both faces of the same sample are captured to reduce any possible reading error. The last selection zone was dedicated to distinguishing between live and dead pupae inside the cocoons. For this, a complex sensor based on photodiodes was used, for which a PCB (Printed Circuit Board) and dedicated software were designed. At the end of sorting, based on different quality grades, the cocoons were directed into different containers with the help of a pneumatic device placed at the end of the belt *(Vasta et al., 2023)*.

The three cameras installed on the prototype were connected to a main personal computer (PC) via an Ethernet cable, each receiving trigger signals to take pictures at a specific moment. The preliminary operations performed before the acquisition process were managed with a GUI (Graphical User Interface) designed and managed in the Java programming language. Using the GUI, various parameters were monitored: the number of photos taken, the status of the cameras, the status of the analog-to-digital converter (ADC), etc., as well as starting or stopping data acquisition. Multi-threading programming techniques were used for the main PC to perform all tasks while simultaneously storing all synchronized images from the cameras and raw data received from the sensor.

Synchronization between the PC, the custom light sensor, and the PLC was achieved using the Modbus Ethernet communication protocol, which was implemented on the Arduino Portenta H7 using the corresponding software library. Based on this protocol, the hierarchy can be summarized as a client (PC) and two servers (Arduino and PLC). To coordinate the movement of all mechanical parts, a Boolean data exchange between the PC and PLC was designed. The correlation between the light sensor and the computer allowed Boolean data to manage the timing of acquisition. To transmit raw data to the Modbus registers of the computer, the same bus was subsequently used *(Vasta et al., 2023).*

RESULTS

The performance of the intelligent mulberry branch cutting device was analyzed in comparison with existing methods, which involve manual cutting using a cutter-type tool. Thus, the operation durations and associated costs are presented comparatively in Figures 17 and 18 *(Kumar et al., 2021).*

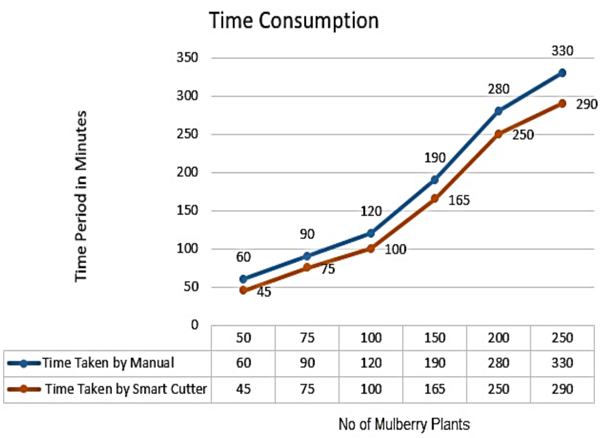

Fig. 17 - The time consumed for performing the cutting operation for a number of mulberry plants (shoots) *(adapted from Kumar et al., 2021)*

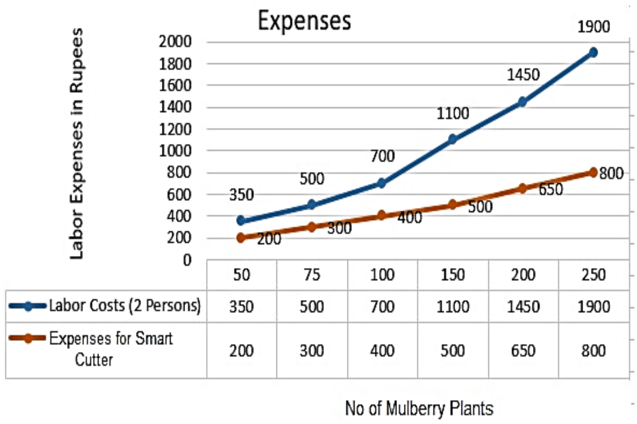

Fig. 18 - The expenses for the cutting operation for a number of mulberry plants (shoots)
(adapted from Kumar et al., 2021)

The intelligent cutting device is operated by a single person, and the results obtained constitute an important premise for increasing productivity and reducing the labor required for feeding silkworms.

For the development of intelligent harvesting, *Zeng et al. (2023*) improved the detection capability of the mulberry leaf node area by replacing the ResNet network with an enhanced ResNeXt network, adding a bottom-up fusion path, as well as a multi-scale regional suggestion network. The optimization efficiency was evaluated through: precision rate (P), recall rate (R), average precision (AP), and F1 score (Table 1). The final detection precision improved by 2.8%, and the F1 score increased by 3.5% compared to the non-enhanced model. The method used in this study can accurately locate the harvesting point, with the leaf nodes obtained through segmentation *(Zeng et al., 2023).*

Table 1

Evaluation results of the model before and after improvement (*Zeng et al. 2023)*

	Precision rate (P) [%]	Recall rate (R) [%]	Average precision (AP) [%]	Scor (F1) [%]
Model Mask R-CNN	84,2	63,2	86,3	72,2
Improved Model Mask R-CNN	86,7	67,1	89,1	75,5

In the study by *Nahiduzzaman et al. (2023),* a PDS CNN model based on XAI (Explainable Artificial Intelligence) was proposed to classify mulberry leaves into categories of healthy, rust-affected, and spotty leaves using a newly created database containing 764 original images, selected by experts. These images were preprocessed into 6000 synthetic images, with an additional 218 and 109 images for testing and validation, respectively. The PDS-CNN model is a unique, parallel, depth-separable CNN (Conventional Neural Network) developed by applying depth-separable convolutional layers to reduce parameters, layers, and size, while enhancing classification performance. The model achieved an accuracy of 95.05 ± 2.86% for three-class classifications and 96.06 ± 3.01% for binary classifications with 0.53M parameters, 8 layers, and 6.3 MB in size. Thus, promising classification performance was achieved, with model interpretability induced by SHAP (Shapley Additive Explanations) and confirmed by sericulture experts.

Due to its specific features, the developed model can be accessible to a wide range of users in sericulture (both professionals and ordinary farmers). Early identification of mulberry leaf diseases leads to significant production savings and benefits for farmers.

In the study by *Jiang et al. (2024),* considering all the necessary elements for using modal analysis in a simulated regime to verify the durability of pinion transmission trees with rack, it was found that they meet the durability requirements. The development of a cheap mobile transport platform that helps handle the frames/trays used in sericulture would substantially reduce labor consumption, improving work efficiency in this field.

The system designed in the study by *Gunasheela et al. (2018)* has a configuration that responds to any climatic changes occurring inside the silkworm rearing enclosure, efficiently responding to stimuli. If the user closes the phone or if the signal strength is low, causing disruptions in the GSM network, the system does not respond adequately. Solutions applied to eliminate these disadvantages include automating the farm so that operations are performed in a timely manner and enabling call redirection. Thus, the system can send messages to a specified alternative number by placing the GSM module in an area where full signal strength is available for communication.

Manjunatha and Neelagar (2018) developed an embedded system model for monitoring and controlling environmental parameters in the silkworm rearing unit, which was tested. The preliminary test demonstrated that the model can work progressively to monitor conditions within the enclosure. Its actuators operate only when necessary, reducing the need for human intervention. The system was implemented smartly, using cost-effective and energy-efficient components. As the system can be relatively easily realized, it is expected to be optimized by using broadband/Wi-Fi and Internet of Things (IoT) for matching processes and securing information.

The system monitoring environmental conditions during the process conducted in a silkworm incubator, as described in the study by *Duque-Torres et al., (2018),* was tested in real time. Data were exported from RPi3 into a simple .txt file (in a Google Drive account). This provided the date, time, temperature measurements from sensor one to sensor nine, humidity measurements from sensor one to sensor nine, and light intensity measurements. Uniformity of environmental conditions inside the incubator is essential. However, the analysis of automatically recorded data revealed the generation of microclimates between the levels of the incubator, highlighted by temperature variation (Fig. 19) and humidity variation (Fig. 20). Besides its low cost, the developed system also features portability, and data visualization and analysis can be performed remotely. Additionally, it is directly programmable, based on open-source codes, which enhances its flexibility compared to commercial tools that only offer predetermined functions.

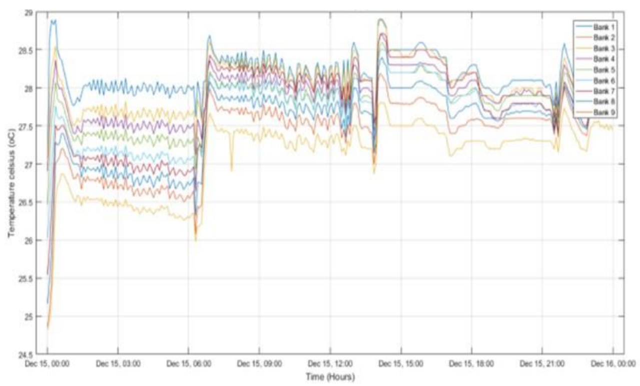

Fig. 19 - Temperature variance graphic
(Duque-Torres et al., 2018)

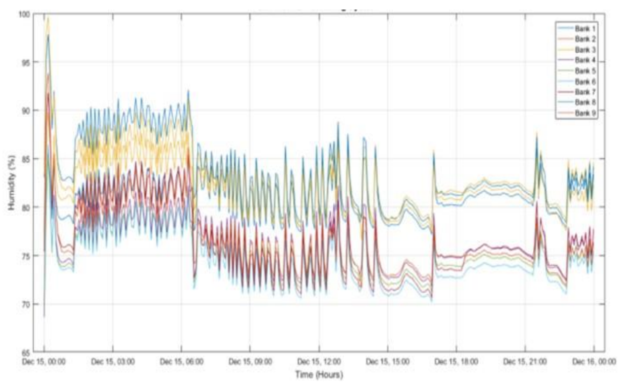

Fig. 20 - Humidity variance graphic
(Duque-Torres et al., 2018)

Using the advanced ecological monitoring and control system in a silkworm rearing incubator proposed by *Kokila et al., (2021),* the egg hatching to larvae occurred between 10-11 days, and the production of silkworm cocoons from larvae lasted 25-30 days. Additionally, productivity was high due to the low mortality rate. Thus, by using this system, farmers have the opportunity to achieve 12-15 iterations of silk production in a year, with reduced labor consumption. Being easy to use and maintaining temperature and humidity with ease, its application scope is expected to expand in the future.

The preliminary test for the Automated Smart Sericulture System from the study by *Arun et al., (2019),* showed that it is capable of successfully monitoring and controlling established state parameters in real time.

These parameters can be monitored remotely, with automation handling the creation of suitable conditions inside. In addition to temperature and humidity sensors, many other sensors for different parameters can be interfaced with this system. Furthermore, image capture can be performed wirelessly, making it more compatible and intelligent. The system's optimization prospects involve deploying the sensor network for sericulture based on CoAP and connecting it to the IPv6 framework for real-time internet monitoring.

The system developed by *Yogeshraj et al. (2022)* can monitor environmental factors (temperature and humidity) and control them using heating systems and fans. Image processing algorithms were used to successfully resize images by detecting edges and performing maximum grouping (Fig. 21). The processed images (Fig.22) allowed differentiation between healthy and unhealthy silkworms, with sick ones being detected. The convolutional neural network-based classification introduced in the proposed scheme improved accuracy and reduced computation time.

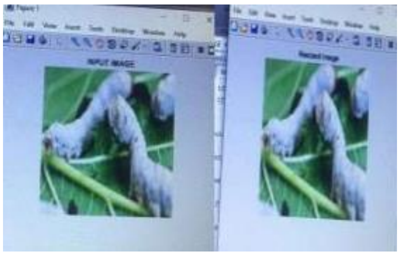

Fig. 21 - Worm resized images
(Yogeshraj et al., 2022)

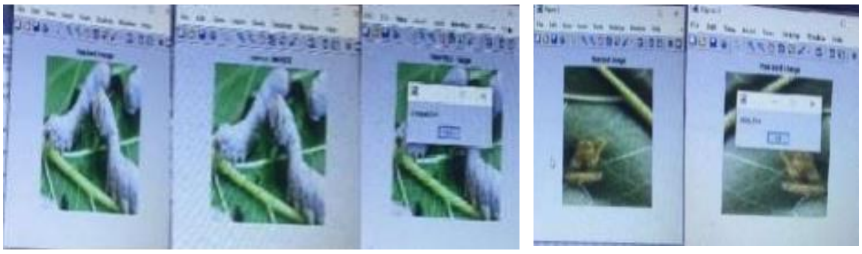

Fig. 22 - Output the healthy and unhealthy silkworms are detected
(Yogeshraj et al., 2022

The effects of drying mulberry silkworm cocoons in an infrared (IR) device at temperatures of 60, 65, and 70°C, and durations of 15, 12, and 10 minutes, are presented in the figures below (Fig. 23, 24, 25) *(Samandarov et al., 2023).*

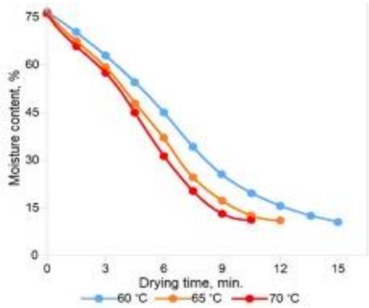

Fig. 23 - Variation in humidity (IR)
(Samandarov et al., 2023)

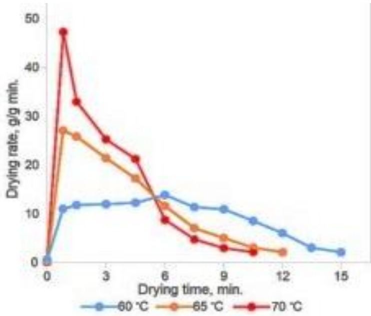

Fig. 24 - Variation in drying speed (IR) *(Samandarov et al., 2023)*

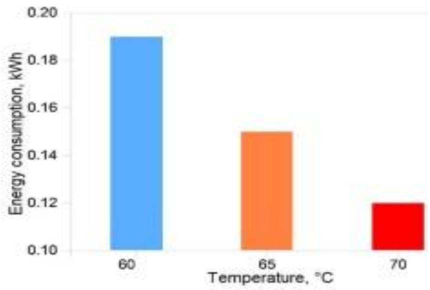

Fig.25 - **Variation in energy consumption (IR**) *(Samandarov et al., 2023)*

For the drying of mulberry silkworm cocoons under the same conditions (IR), with the addition of exposure to ultrasonic (US) waves, the effects are presented in Figures 26, 27, 28 *(Samandarov et al., 2023).*

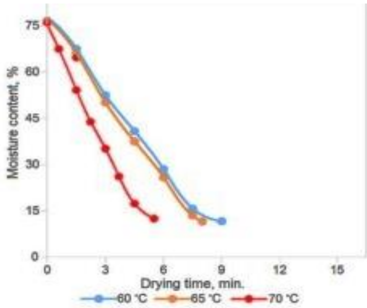

Fig. 26 - **Variation in humidity (IR+US)**
(Samandarov et al., 2023)

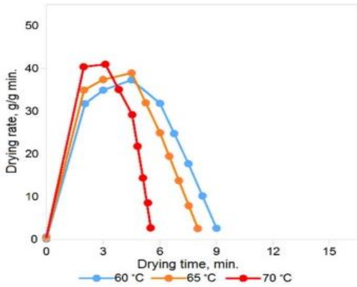

Fig. 27 - **Variation in drying speed (IR+US)**
(Samandarov et al., 2023)

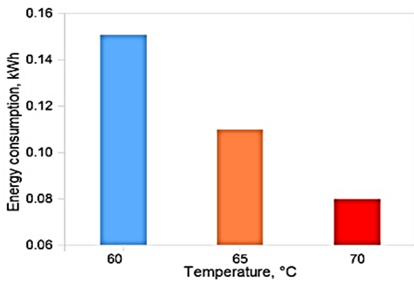

Fig. 28 - Variation in energy consumption (IR+US)
(Samandarov et al., 2023)

Combining the two methods (Infrared IR and Ultrasound US) results in faster and more efficient drying, reducing energy consumption, as ultrasound can affect the microstructure of mulberry cocoons. Thus, the optimal drying conditions were determined to be: temperature 70 °C, ultrasound frequency 50 Hz, and exposure time of approximately 5 minutes *(Samandarov et al., 2023).*

The performance of the prototype machine for separating cocoons by gender is evaluated based on accuracy, robustness, and speed. Table 2 shows the performance metrics calculated, namely: Accuracy, True Male Rate (TMR), True Female Rate (TFR), Male Predictive Rate (MPR), and Female Predictive Rate (FPR), with reference to both training and test phases for CSR2 and Pure Mysore cocoons *(Raj et al., 2019).*

Table 2

Performance metrics (PM) obtained for CSR2 and pure Mysore cocoons from SVM

(*Raj et al. 2019)*

Performance metrics (PM)	**Training**		**Testing**	
	CSR2	**Pure Mysore**	**CSR2**	**Pure Mysore**
Accuracy	0.9259	0.9778	0.8649	0.9355
True Male Rate (TMR)	0.9642	1.000	0.8947	0.9286
True Female Rate (TFR)	0.8846	0.9583	0.8333	0.9412
Male Predictive Rate (MPR)	0.9000	0.9545	0.85	0.9286
Female Predictive Rate (FPR)	0.9583	1.000	0.8824	0.9412

During the gender separation operation, a cocoon moves from the VCM module of the machine to the FEM module in an average time of approximately 4.6 seconds. It remains there for about 2.2 seconds, consuming 1 second to acquire shape characteristics and 1.2 seconds for weight characteristics. It then reaches the collection tray through the HCM in approximately 3.6 to 4.1 seconds. Thus, a cocoon moves from the hopper to the collection tray in approximately 10.9 seconds. The machine can classify about 5.5 cocoons per minute, which translates to about 330 cocoons per hour, or approximately 2640 cocoons per shift (8 hours). With an average cocoon weight of 1.3 grams, the machine can classify about 3.4 kg of cocoons per shift, with an accuracy of approximately 86.48% to 93.54% and a repeatability of 88%. The results demonstrate the machine's potential to enhance the productivity of gender classification of cocoons in silk farming centers, as well as in the industry. The cocoon gender sorting machine, which does not damage the casing, represents a significant step forward in reducing human intervention and automating operations in sericulture *(Raj et al., 2019).*

The performance of the automated prototype for Bombyx Mori cocoon sorting varied depending on the selection parameters considered. Following the tests and improvements in both software and hardware, the equipment achieved a maximum sorting frequency of 80 cocoons per minute. The equipment also achieved optimal performance for oversized cocoons, but performance for undersized cocoons was lower due to their tendency to be positioned vertically in the capsule (Fig. 29), which affected the accurate image capture for identification *(Vasta et al., 2023).*

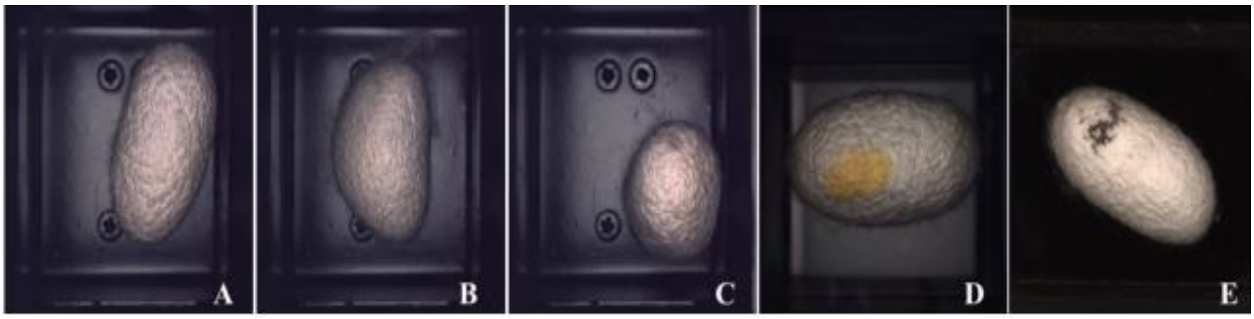

Fig. 29 - The position of cocoons inside their housing *(Vasta et al., 2023).*

A - regular cocoon; B - defective shape; C - incorrect size due to positioning; D - stained at the top (large orange spot); E - stained at the bottom (black spot)

The performance regarding the dimensional selection of cocoons is presented in Table 3 *(Vasta et al., 2023).*

Table 3

The equipment performances (defective cocoons marked as such) (*Vasta et al. 2023)*

Parameters	True Positive Percentage [%]
Oversized cocoons (larger than 450 mm^2)	87.8
Undersized cocoons (smaller than 300 mm^2)	29.6
Undersized cocoons with no vertically positioned ones	90.0

The performance metrics of the prototype in dead-cocoon selection based on the logistic regression model from the photodiode matrix were: classification ratio and cross-validation accuracy. The correct classification ratio achieved for dead-cocoon selection was 81.5% on the training set and 78.4% on the test set. Cross-validation with 100 steps was also performed, yielding an average accuracy of 80.7% for training and 81.6% for testing. The development and testing of the equipment allowed for a detailed study of the patented idea. Additionally, its encouraging performance contributed to identifying various aspects, especially practical ones, that should be optimized and could be the subject of further research *(Vasta et al. 2023).*

CONCLUSIONS

This paper provides a synthesis of recent research on innovative technical solutions across various sectors related to sericulture. Generally, in agriculture, the use of modern machinery, equipment, and production systems ensures sustainability and enhances both production and quality. Technological innovations play a crucial role in the employment opportunities offered by sericulture.

Despite a global decline in cocoon and silk production, current trends make natural silk fibers highly favored in the fashion and textile industries, as well as in numerous other fields, due to their unique characteristics.

The technical solutions presented are highly accessible to users, aiming to minimize human intervention in silk production or increase the productivity of operations that cannot maintain consistent performance levels when done manually. They also focus on implementing innovative ideas or smart applications to enhance the added value of sericulture products. These innovative solutions provide a significant basis for future research aimed at developing and modernizing specific technologies and revitalizing or resuming sericulture activities in geographic areas where they were once intensively practiced in the past century.

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