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ANALYSIS OF OIL EXTRACTION FROM SILKWORM PUPAE USING SUPERCRITICAL CO_2 AS A CONTROL OBJECT AND SELECTION OF INTELLIGENT CONTROL PARAMETERS

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Annotatsiya. Ushbu maqolada pilla g‘umbagidan o‘ta kritik karbonat angidrid (CO_2) yordamida moy ajratish jarayoni boshqarish obyekti sifatida tahlil qilinadi. Pilla g‘umbagi ipakchilik sanoatining ikkilamchi xomashyosi hisoblanadi va uning tarkibidagi lipidlar hamda biologik faol moddalardan samarali foydalanish oziq-ovqat, farmatsevtika va kosmetika sanoati uchun katta ahamiyatga ega. An’anaviy ekstraksiya usullari ko‘pincha bir qator cheklovlar bilan bog‘liq bo‘lib, ular yakuniy mahsulot tarkibida erituvchi qoldiqlarining saqlanib qolishi, biologik faol moddalarning parchalanishi hamda moy ajratish samaradorligining yetarli darajada bo‘lmasligida namoyon bo‘ladi. O‘ta kritik CO_2 ekstraksiyasi esa past toksiklik, yonuvchan emaslik, yuqori selektivlik va ekologik xavfsizlik kabi afzalliklarga ega. Ushbu tadqiqotda ekstraksiya jarayoniga ta’sir qiluvchi asosiy texnologik omillar, jumladan bosim, harorat, CO_2 sarfi, ekstraksiya davomiyligi, xomashyoning maydalanish darajasi va g‘ovakliligi tahlil qilindi. Jarayon murakkab, nochiziqli va ko‘p parametrli boshqarish obyekti sifatida qaralib, boshqariluvchi, boshqaruvchi va g‘alayonlantiruvchi o‘zgaruvchilar aniqlab olindi. Shuningdek, moy chiqimi va ekstrakt konsentratsiyasini barqarorlashtirish uchun noaniq mantiq hamda ANFIS asosidagi intellektual boshqarish yondashuvlaridan foydalanish imkoniyatlari asoslandi. Texnologik tavsifga ko‘ra, jarayonning asosiy ish parametrlari ekstraksiya konturidagi bosim va harorat bo‘lib, ular CO_2 ning erituvchanlik xossalariga hamda ajratib olingan moyning yakuniy tarkibiga bevosita ta’sir ko‘rsatadi.

Kalit so‘zlar: pilla g‘umbagi, o‘ta kritik CO_2, moy ekstraksiyasi, karbonat angidrid, boshqarish obyekti, intellektual boshqarish, ANFIS, noaniq mantiq, bosim, harorat, CO_2 sarfi, ekstraksiya davomiyligi, moy chiqimi.

Аннотация. В данной статье процесс извлечения масла из куколок тутового шелкопряда с использованием сверхкритического диоксида углерода (CO_2) рассматривается как объект управления. Куколки тутового шелкопряда являются вторичным сырьём шелководческой промышленности, а эффективное использование содержащихся в них липидов и биологически активных соединений имеет важное значение для пищевой,

фармацевтической и косметической промышленности. Традиционные методы экстракции часто связаны с рядом ограничений, включая наличие следов растворителей в конечном продукте, разрушение биологически активных веществ и недостаточную эффективность извлечения масла. В отличие от них, сверхкритическая CO_2-экстракция обладает такими преимуществами, как низкая токсичность, негорючесть, высокая селективность и экологическая безопасность. В исследовании проанализированы основные технологические факторы, влияющие на процесс экстракции, в том числе давление, температура, расход CO_2, продолжительность экстракции, степень измельчения сырья и его пористость. Процесс рассмотрен как сложный, нелинейный и многопараметрический объект управления, при этом были выделены управляемые, управляющие и возмущающие переменные. Кроме того, обоснована возможность применения подходов интеллектуального управления на основе нечёткой логики и ANFIS для стабилизации выхода масла и концентрации экстракта. Согласно технологическому описанию, основными рабочими параметрами процесса являются давление и температура в экстракционном контуре, которые непосредственно влияют на растворяющую способность CO_2 и конечный состав извлечённого масла.

Ключевые слова: куколки тутового шелкопряда, сверхкритический CO_2, экстракция масла, диоксид углерода, объект управления, интеллектуальное управление, ANFIS, нечёткая логика, давление, температура, расход CO_2, продолжительность экстракции, выход масла

Abstract. This article analyzes the process of oil extraction from silkworm pupae using supercritical carbon dioxide (CO_2) as a control object. Silkworm pupae are considered a secondary raw material of the sericulture industry, and the efficient utilization of their lipids and biologically active compounds is of significant importance for the food, pharmaceutical, and cosmetic industries. Conventional extraction methods are often associated with several limitations, including residual solvent traces in the final product, degradation of biologically active compounds, and insufficient oil recovery efficiency. In contrast, supercritical CO_2 extraction offers several advantages, such as low toxicity, non-flammability, high selectivity, and environmental safety. In this study, the main technological factors affecting the extraction process were analyzed, including pressure, temperature, CO_2 flow rate, extraction duration, particle size reduction of the raw material, and porosity. The process was considered as a complex, nonlinear, and multi-parameter control object, and the controlled, manipulated, and disturbance variables were identified. In addition, the feasibility of using fuzzy logic and ANFIS-based intelligent control approaches to stabilize oil yield and extract concentration was substantiated.

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According to the technological description, the main operating parameters of the process are the pressure and temperature in the extraction circuit, which directly influence the solubility properties of CO_2 and the final composition of the extracted oil.

Keywords. silkworm pupae, supercritical **CO_2**, oil extraction, carbon dioxide, control object, intelligent control, ANFIS, fuzzy logic, pressure, temperature, **CO_2** flow rate, extraction duration, oil yield.

INTRODUCTION.

Currently, the demand for natural, environmentally safe products rich in biologically active compounds is steadily increasing in the food, pharmaceutical, and cosmetic industries. In particular, the production of value-added products through the deep processing of secondary raw materials generated in agriculture and the sericulture industry is regarded as an important scientific and practical task. Silkworm pupae represent one of such promising secondary raw materials, as the efficient utilization of their lipids, fatty acids, and biologically active components enables the production of valuable industrial products. Previous studies have emphasized that supercritical CO_2 extraction is an efficient and environmentally safe approach for recovering oil from silkworm pupae, while also highlighting the need to optimize the key process parameters. [1].

Conventional methods, such as pressing and extraction with organic solvents, have long been used for recovering oil from silkworm pupae. However, these methods do not always provide high extraction efficiency; in some cases, solvent residues may remain in the final product, biologically active compounds may undergo qualitative degradation, or environmental safety requirements may not be fully satisfied. Supercritical CO_2 extraction helps to overcome these limitations, since CO_2 is non-flammable, has low toxicity, is chemically inert, and can be relatively easily separated from the extract by changing the pressure or temperature. Wang et al. demonstrated that high extraction efficiency in silkworm pupae oil recovery using supercritical CO_2 can be achieved at 25 MPa, 35 °C, and an extraction time of 3 h [2].

In the supercritical CO_2 extraction process, pressure, temperature, CO_2 flow rate, and extraction duration are among the most important technological factors. Wei et al. optimized the extraction of silkworm pupae oil using response surface methodology and determined the optimal conditions as 324.5 bar pressure, 39.6 °C temperature, 131.2 min extraction time, and 19.3 L/h CO_2 flow rate. [3]. Studies on oak silkworm pupae oil have also identified pressure, temperature, extraction time, and CO_2 flow rate as the main factors to be optimized in supercritical CO_2 extraction. [4].

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In the oil extraction process from silkworm pupae, the solvent properties of supercritical CO_2 mainly depend on pressure and temperature. An increase in pressure raises the density of CO_2, thereby enhancing its solvent capacity toward lipid components. Temperature, on the one hand, increases the diffusion rate, while on the other hand, it affects CO_2 density. Therefore, considering the combined effect of pressure and temperature is essential for the scientifically grounded control of the extraction process. The Chrastil model is widely used to evaluate the solubility of compounds in supercritical media, whereas the Sovová model is commonly applied to analyze the kinetics of mass release from the cellular structure of solid raw materials. [5].

Extraction efficiency is not determined solely by pressure and temperature. CO_2 flow rate, extraction duration, degree of raw material grinding, particle size, porosity, moisture content, mass transfer coefficient, and diffusion conditions also directly affect the final oil yield and extract quality. Therefore, the oil extraction process from silkworm pupae should not be considered as a simple linear object, but rather as a complex, nonlinear, multi-parameter, and interconnected technological system. Studies on the prediction of oil yield in supercritical extraction processes using neural networks and adaptive neuro-fuzzy models indicate that intelligent modeling approaches can be effective for such processes. [6].

Effective control of such complex objects cannot always be achieved with sufficient accuracy using classical control methods, since the relationships between the process parameters are nonlinear and certain process characteristics vary over time. Fuzzy logic-based control approaches make it possible to evaluate the state of a complex technological object through linguistic rules, support decision-making under uncertainty, and adapt control actions to changing process conditions. In a study co-authored by Alisher Jabborov, the problem of controlling nonlinear dynamic objects in intelligent systems using fuzzy logic was examined; therefore, this approach can also serve as a methodological basis for complex processes such as the extraction of silkworm pupae oil using supercritical CO_2. [7].

Computer-based modeling of technological processes, evaluation of parameter effects, and determination of optimal operating conditions are among the key directions of modern automation research. In another study co-authored by Komil Usmanov, the drying process of medicinal plants in a cabinet-type solar dryer was mathematically modeled, and the possibilities of evaluating process dynamics and optimizing operating conditions in the MATLAB/Simulink environment were demonstrated by taking into account heat and mass transfer mechanisms. [8]. This, in turn, provides a scientific basis for applying modeling

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techniques and selecting intelligent control parameters in the oil extraction process from silkworm pupae.

From this perspective, the aim of this article is to analyze the oil extraction process from silkworm pupae using supercritical CO_2 as a control object, to identify the main input and output parameters of the process, and to select the most significant manipulated variables for an intelligent control system. This approach enables a systems-based assessment of the effects of pressure, temperature, CO_2 flow rate, and extraction duration on oil yield, while also providing a basis for stabilizing the extraction process, reducing energy consumption, and developing optimal technological regimes.

MATERIALS AND METHODS.

Silkworm pupae, a secondary raw material of the sericulture industry, were selected as the research material. Silkworm pupae contain lipids, fatty acids, protein substances, and biologically active components; therefore, the extraction of oil from this material using an environmentally safe method is of practical importance for the food, pharmaceutical, and cosmetic industries. The technological process of oil extraction from silkworm pupae using supercritical carbon dioxide (CO_2) was considered as the research object. The selection of CO_2 as an extractant in this process is justified by its low toxicity, non-flammability, chemical inertness, and absence of harmful solvent residues in the final product. In addition, CO_2 can be easily separated from the extract when the pressure or temperature is reduced, which enables the process to be organized in a closed cycle.

Previous studies have evaluated pressure, temperature, CO_2 flow rate, and extraction duration as the main technological factors influencing the extraction of oil from silkworm pupae using supercritical CO_2. In particular, Wei et al. optimized the extraction of silkworm pupae oil using response surface methodology and determined the optimal conditions as a pressure of 324.5 bar, a temperature of 39.6 °C, an extraction time of 131.2 min, and a CO_2 flow rate of 19.3 L/h. [9]. Wang et al. demonstrated that high extraction efficiency in the recovery of oil from silkworm pupae using supercritical CO_2 can be achieved under the following operating conditions: a pressure of 25 MPa, a temperature of 35 °C, and an extraction time of 3 h. [10].

In analyzing the technological process, the preparation stage of silkworm pupae prior to extraction was also taken into account. In this regard, the moisture content, degree of particle size reduction, particle size, and porosity of the raw material were considered important factors affecting the mass transfer process. An increase in the degree of particle size reduction expands the interfacial contact area and accelerates the transfer of oil-containing components into the CO_2 stream. However, excessive grinding of the raw material may increase hydrodynamic

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resistance within the bed, adversely affect the uniform distribution of the extractant flow, and complicate internal diffusion conditions. Therefore, the raw material preparation stage was evaluated as part of the disturbance factors of the control object.

The experimental setup was considered as a technological system consisting of a CO_2 cylinder, compressor, condenser, heat exchanger, high-pressure extractor, and separator. During the process, pre-ground silkworm pupae are loaded into the extractor, the extractor is hermetically sealed, the system is filled with CO_2, and carbon dioxide is compressed to the required pressure using a compressor. Subsequently, CO_2 is supplied to the extractor through the condenser and heat exchanger. In its supercritical state, CO_2 passes through the silkworm pupae bed, dissolves the oil-containing components, and transports them to the separator. In the separator, as a result of pressure reduction, CO_2 returns to the gaseous state, while the oil is separated as an individual fraction. According to the given technological description, the main technical characteristics of the setup include an extractor volume of 1.25 L, a separator volume of 3.0 L, a maximum pressure of 15 MPa, a maximum temperature of 60 °C, and a maximum specific CO_2 flow rate of 4.0 L/min.

A systems approach was applied to analyze the process as a control object. In this approach, the input, output, and disturbance factors of the technological process were classified into separate groups. The manipulated input parameters included the extractant pressure P, extractant temperature T, CO_2 flow rate QCO_2, and extraction duration τ. The controlled output parameter was defined as either the oil yield Y or the concentration of the final extract Scon. The disturbance factors included the degree of raw material grinding, particle radius, porosity, moisture content, CO_2 viscosity, diffusion coefficient, and mass transfer conditions. In the proposed conceptual model, temperature, pressure, extractant density, extraction duration, raw material mass, and the amount of CO_2 were also identified as the main variables affecting the process.

The main operating parameters of the extraction process are determined by the pressure and temperature within the extraction circuit. Variations in these parameters directly affect the density of CO_2, its solvent properties, and the final composition of the extracted oil. An increase in pressure enhances the density of CO_2 and improves its ability to dissolve oil-containing components. Temperature, in turn, positively influences the diffusion rate while also causing changes in CO_2 density. Therefore, pressure and temperature were considered interrelated manipulated parameters. The source also identifies pressure and temperature as the principal operating parameters of the process and notes that their effects on

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solubility can be analyzed using the Chrastil model, while the mass transfer kinetics from solid cellular structures can be evaluated using the Sovová model.

In this study, the parameter ranges for the ANFIS model were determined based on the technical capabilities of the experimental setup and the results reported in the literature on supercritical CO_2 extraction. For the model, pressure was accepted in the range of 8–15 MPa, temperature in the range of 35–60 °C, CO_2 flow rate in the range of 1–4 L/min, and extraction duration in the range of 60–180 min. These values were selected so as not to exceed the maximum pressure, maximum temperature, and CO_2 flow rate limits of the experimental setup. In addition, the importance of pressure, temperature, and extraction time in the recovery of oil from silkworm pupae, as confirmed in the literature, provided the basis for selecting these parameters as the main input signals of the model.

Table 1.

Operating parameters accepted for the ANFIS model

Parameter	Symbol	Range accepted for the model	Role in the process
Extractant pressure	P	8–15 MPa	Determines CO_2 density and solvent capacity
Extractant temperature	T	35–60 °C	Affects the diffusion rate and CO_2 density
CO_2 flow rate	QCO_2	1–4 L/min	Determines the intensity of mass transfer
Extraction duration	τ	60–180 min	Influences the formation of oil yield
Oil yield	Y	% or g/100 g	Main output indicator of the model
Extract concentration	S_{con}	Based on experimental results	Evaluates the quality of the final product

Fuzzy logic and neuro-fuzzy approaches were adopted as the methodological basis for selecting intelligent control parameters. In complex technological processes, the presence of multiple inputs and outputs, the nonlinear relationships between parameters, and the time-varying nature of process characteristics require the application of intelligent control methods. A fuzzy logic-based approach makes it possible to evaluate the state of a technological object, formulate a linguistic rule base, and model the decision-making process in complex control objects. [10].

The input variables selected for the ANFIS model were P, T, QCO_2, and τ. The output variable was defined as the oil yield Y. This selection is justified by the fact that pressure determines the density and solvent capacity of CO_2, temperature

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affects both the diffusion rate and extract density, the CO_2 flow rate modifies the intensity of mass transfer, and extraction duration is the main time-dependent factor governing the amount of oil recovered. In developing the ANFIS model, the experimental dataset is planned to be divided into training, validation, and testing subsets. To evaluate the predictive accuracy of the model, the root mean square error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2) are recommended as performance criteria.

The general structural scheme of the oil extraction process from silkworm pupae as a control object is presented in Figure 1.

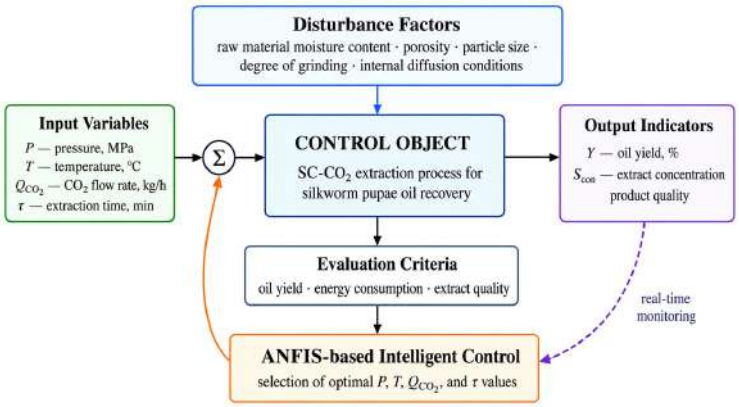


Figure 1. Structural scheme of the oil extraction process from silkworm pupae using supercritical CO_2 as a control object.

The overall methodological sequence of the study was defined as follows: in the first stage, the physicochemical nature of silkworm pupae as a raw material and the supercritical CO_2 extraction process was analyzed; in the second stage, the main operating parameters of the technological setup were specified; in the third stage, the manipulated, controlled, and disturbance variables were classified; and in the fourth stage, the input and output variables for the ANFIS model were selected. This methodological approach makes it possible to evaluate the oil extraction process from silkworm pupae using supercritical CO_2 as a complex, nonlinear, and multi-parameter control object.

RESULTS AND DISCUSSION.

A systems-based analysis of the oil extraction process from silkworm pupae using supercritical CO_2 as a control object showed that this process is a multi-parameter, nonlinear, and interconnected technological system. The process outcome is not determined by a single factor alone, but rather by the combined effects of pressure, temperature, CO_2 flow rate, extraction duration, raw material moisture content, particle size, porosity, and diffusion conditions. The given technological description also characterizes supercritical CO_2 extraction as a complex, dynamic, nonlinear, and multi-connected system. Therefore, the separate identification of manipulated and controlled parameters, the determination of their

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technological limits, and the selection of input–output variables suitable for an intelligent control model represent important results for this process.

As a result of the analysis, the extractant pressure P, extractant temperature T, CO_2 flow rate QCO_2, and extraction duration τ were selected as the manipulated input variables. The oil yield Y, extract concentration S_{con}, and product quality were accepted as the output indicators. Raw material moisture content, porosity, particle size, degree of grinding, diffusion conditions, and mass transfer conditions were evaluated as disturbance factors. The identification of these factors serves to form the information base required for the ANFIS-based model.

Table 1.

Main parameters of the supercritical CO_2 extraction process as a control object

Parameter group	Symbol	Parameter name	Role in the process
Input factor	P	Pressure	Determines CO_2 density and solvent capacity
Input factor	T	Temperature	Affects the diffusion rate and CO_2 density
Input factor	QCO_2	CO_2 flow rate	Determines the intensity of mass transfer
Input factor	τ	Extraction duration	Determines the duration of oil release
Output indicator	Y	Oil yield	Represents the efficiency of the process
Output indicator	Scon	Extract concentration	Characterizes the quality of the final product
Disturbance factor	—	Moisture content, porosity, particle size	Affects process stability and mass transfer

Taking into account the capabilities of the technological setup, the operating parameter ranges for the model were defined. According to the given equipment description, the extractor volume is 1.25 L, the separator volume is 3.0 L, the maximum pressure is 15 MPa, the maximum temperature is 60 °C, and the maximum specific CO_2 flow rate is 4.0 L/min. Based on these technical limits, the pressure range for the ANFIS model was accepted as 8–15 MPa, the temperature range as 35–60 °C, the CO_2 flow rate as 1–4 L/min, and the extraction duration as 60–180 min. These values do not exceed the safe operating limits of the experimental setup and provide a sufficient parameter space for the model.

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Table 2.

Operating parameter ranges accepted for the ANFIS model

Parameter	Symbol	Accepted range	Justification
Pressure	P	8–15 MPa	Does not exceed the maximum pressure of the setup, 15 MPa
Temperature	T	35–60 °C	Does not exceed the maximum temperature of the setup, 60 °C
CO_2 flow rate	QCO_2	1–4 L/min	Limited by the maximum CO_2 flow rate of the setup, 4.0 L/min
Extraction time	τ	60–180 min	Consistent with the time ranges reported in the literature
Output indicator	Y	% or g/100 g	Used to evaluate oil yield

The results reported in the literature also confirm the validity of the selected parameters. Wei et al. optimized the extraction of silkworm pupae oil using supercritical CO_2 based on response surface methodology and determined the optimal conditions as a pressure of 324.5 bar, a temperature of 39.6 °C, an extraction time of 131.2 min, and a CO_2 flow rate of 19.3 L/h. [11]. Wang et al. showed that high extraction efficiency in the recovery of oil from silkworm pupae using supercritical CO_2 can be achieved at a pressure of 25 MPa, a temperature of 35 °C, and an extraction time of 3 h. [12]. These data indicate that pressure, temperature, CO_2 flow rate, and extraction time are the most important manipulated parameters in the extraction of silkworm pupae oil.

Pressure is one of the key factors affecting the process. As pressure increases, the density of CO_2 also increases, thereby enhancing its ability to dissolve lipid components. Therefore, an increase in pressure generally has a positive effect on oil yield. However, excessive pressure must be limited in terms of equipment safety, energy consumption, and technological stability. In the present study, the pressure range of 8–15 MPa was selected in accordance with the technical capabilities of the experimental setup.

The effect of temperature is more complex than that of pressure. An increase in temperature enhances the diffusion rate and accelerates the transfer of oil-containing components from the internal structure of the raw material into the CO_2 stream. At the same time, a rise in temperature may also lead to a decrease in CO_2 density. Therefore, when selecting the optimal temperature, the balance between diffusion rate and solvent capacity must be taken into account. For this reason, temperature was accepted as an independent input parameter in the ANFIS model.

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The CO_2 flow rate determines the intensity of the mass transfer process. As the flow rate increases, the velocity of the extract passing through the raw material bed also increases, thereby accelerating the transport of dissolved oil components to the separator. However, high CO_2 flow rates may increase compressor load and energy consumption. Therefore, the CO_2 flow rate should be evaluated not only in terms of increasing oil yield but also together with the criterion of energy efficiency. In the present study, the CO_2 flow rate was accepted in the range of 1–4 L/min, since the maximum flow rate specified in the given equipment description is 4.0 L/min.

Extraction duration plays an important role in the formation of oil yield. In the initial stages of the process, free oil components located near the surface of the raw material are rapidly extracted by the CO_2 flow. In the subsequent stages, however, internal diffusion resistance increases, and the rate of oil release decreases. Therefore, excessively prolonging the extraction time is not always economically efficient. This indicates that not only oil yield but also energy consumption should be included among the evaluation criteria.

The degree of raw material grinding and particle size are of particular importance among the disturbance factors. As the degree of grinding increases, the interfacial contact area expands and mass transfer is intensified. However, excessively fine particles may lead to compaction of the raw material bed, non-uniform distribution of the extractant flow, and increased hydrodynamic resistance. Therefore, raw material preparation parameters were not considered as direct control signals, but rather as disturbance factors to be taken into account in the ANFIS model.

As a result of the analysis, oil yield, energy consumption, and extract quality were selected as the evaluation criteria. Oil yield reflects the technological efficiency of the process, energy consumption characterizes its economic efficiency, and extract quality determines the practical value of the final product. Therefore, when selecting the optimal operating regime, the intelligent control system should be oriented not only toward maximizing oil yield, but also toward reducing energy consumption and stabilizing product quality.

The input variables selected for the ANFIS model were P, T, QCO_2, and τ. At the initial stage, the oil yield Y was accepted as the output variable. In subsequent stages, the model may be extended by incorporating S_{con} — extract concentration — and product quality indicators. The application of fuzzy logic and neuro-fuzzy approaches enables the representation of nonlinear relationships between parameters in complex technological objects. The use of this approach in the control of technological objects has also been considered in previous studies. [13].

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Table 3.

Input and output variables selected for the ANFIS model

Model element	Symbol	Variable name	Reason for selection
Input	P	Pressure	Directly affects CO_2 solubility and density
Input	T	Temperature	Determines the diffusion rate and CO_2 density
Input	QCO_2	CO_2 flow rate	Changes the intensity of mass transfer
Input	τ	Extraction time	Represents the duration of oil release
Output	Y	Oil yield	Main indicator for evaluating process efficiency

Table 4.

Main scientific results obtained from the systems analysis

No.	Direction of analysis	Obtained result
1	Control object	The oil extraction process from silkworm pupae using supercritical CO_2 was defined as a multi-parameter and nonlinear object
2	Input parameters	P, T, QCO_2, and τ were selected as the main manipulated variables
3	Output indicators	Y — oil yield, S_{con} — extract concentration, and product quality were selected
4	Disturbance factors	Moisture content, porosity, particle size, degree of grinding, and diffusion conditions were identified
5	Evaluation criteria	Oil yield, energy consumption, and extract quality were defined as the main criteria
6	Control approach	An ANFIS-based intelligent control model was recommended

The discussion results indicate that evaluating the oil extraction process from silkworm pupae using supercritical CO_2 as a simple linear object is insufficient. In this process, pressure, temperature, CO_2 flow rate, and extraction duration influence the system in an interrelated manner. In addition, the physical state of the raw material, particle size, and porosity alter mass transfer conditions and directly affect the process outcome. Therefore, the ANFIS-based approach is recommended

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as an appropriate intelligent control tool for selecting the optimal values of P, T, QCO_2, and τ in the extraction of silkworm pupae oil.

At this stage, the input and output parameters for the ANFIS model were selected, and a systems analysis of the control object was carried out. In the next stage of the study, it is planned to train the ANFIS model using experimental data, evaluate the model accuracy based on RMSE, MAE, and R^2 criteria, and determine the optimal technological regimes. This approach will make it possible to formulate specific control decisions aimed at increasing oil yield, reducing energy consumption, and stabilizing extract quality in subsequent research stages.[14]

Overall, the results showed that the main manipulated parameters for the oil extraction process from silkworm pupae using supercritical CO_2 are pressure, temperature, CO_2 flow rate, and extraction duration. Based on the technical limits of the experimental setup, the ranges of 8–15 MPa, 35–60 °C, 1–4 L/min, and 60–180 min were selected for the model. These parameters provide a methodological basis for developing an ANFIS-based intelligent control system aimed at accounting for the nonlinear characteristics of the process, increasing oil yield, reducing energy consumption, and stabilizing extract quality.

CONCLUSION.

In this article, the process of oil extraction from silkworm pupae using supercritical CO_2 was systematically analyzed as a control object, and the main parameters required for developing an intelligent control model were selected. The analysis showed that this process is a multi-parameter, nonlinear, and interconnected technological object, whose efficiency directly depends on pressure, temperature, CO_2 flow rate, extraction duration, and the physicochemical properties of the raw material.

The manipulated input parameters were selected as P — pressure, T — temperature, QCO_2 — CO_2 flow rate, and τ — extraction duration. The output indicators were defined as Y — oil yield, S_{con} — extract concentration, and product quality. Raw material moisture content, porosity, particle size, degree of grinding, diffusion conditions, and mass transfer conditions were identified as disturbance factors.

Taking into account the technical capabilities of the experimental setup, the pressure range for the ANFIS model was accepted as 8–15 MPa, the temperature range as 35–60 °C, the CO_2 flow rate as 1–4 L/min, and the extraction duration as 60–180 min. These parameters provide a methodological basis for developing an intelligent control model aimed at increasing oil yield, reducing energy consumption, and stabilizing extract quality in the supercritical CO_2 extraction process.

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The results of the study indicate that the ANFIS-based approach can serve as an effective tool for considering nonlinear relationships in the oil extraction process from silkworm pupae and for selecting optimal technological regimes. In future research, it is advisable to train the ANFIS model using experimental data, evaluate its accuracy based on RMSE, MAE, and R^2 criteria, and develop an optimal control algorithm.

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