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MODELING OF A FIBER-OPTIC HUMIDITY SENSOR BASED ON A CARRAGEENAN-COATED FABRY-PEROT INTERFEROMETER

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Abstract. *The article presents the results of mathematical modeling of a fiber-optic humidity sensor based on an in-fiber Fabry–Perot interferometer with a sensitive coating made of the carrageenan biopolymer. The physical model of the sensor describes the change in the optical path in the resonator during swelling of the polymer layer under the influence of water vapor. The three-parameter Guggenheim-Anderson-de Boer model is used to describe the sorption isotherm. A multi-level temperature compensation algorithm is proposed, which reduces the temperature error by more than 300 times. The adaptive Adam optimizer is used to find the optimal design parameters (cavity length, coating thickness and refractive index). The optimization results showed the following: cavity length of 50.0 μm, coating thickness of 5.0 μm, sensitivity of 150.5 pm/%RH with a determination coefficient of $R^2 = 0.9512$. The response time τ is 214 ms. The residual temperature error after compensation does not exceed 0.15% RH in the range of –20 to +60 °C. The results demonstrate the potential of the carrageenan coating for the creation of highly sensitive, biocompatible fiber-optic humidity sensors.*

Keywords: *fiber optic sensor; Fabry-Perot interferometer; relative humidity; carrageenan; GAB isotherm; temperature compensation.*

Introduction

Measuring relative humidity is a critical task in meteorology, medicine, the food industry, semiconductor manufacturing, and many other fields [1]. Traditional electronic humidity sensors–capacitive and resistive–have proven themselves to be effective, but are susceptible to electromagnetic interference, struggle to operate in aggressive environments, and require electrical power directly at the sensing element [2]. Fiber-optic sensors overcome these drawbacks: they are lightweight, passive, resistant to electromagnetic fields, and suitable for use in hazardous areas [3, 4].

Among the various fiber sensor configurations, the Fabry–Perot interferometer (FPI) stands out for its compactness, high sensitivity to changes in optical path length, and comparative ease of fabrication [5, 6]. The FPI sensor's sensitivity to humidity is ensured by applying a thin polymer coating those swells upon absorbing moisture, changing the resonator length and shifting the interference fringes [7, 8]. A key issue in the design is the choice of coating material, which determines sensitivity, linearity, and response time [5].

A key factor in the efficiency of such sensors is the choice of a moisture-sensitive coating [7, 8]. The prototype of the present work was a chitosan-based sensor proposed by Chen et al. [9], which achieved a sensitivity of 130.0 pm/%RH using a chitosan coating with a thickness of about 6.2 μm. However, chitosan requires special chemical treatment during application. In contrast, carrageenan, a natural sulfated polysaccharide obtained from red algae, has high hygroscopicity,

good adhesion to quartz, biocompatibility, and ease of formation of thin films [10-13]. According to the Guggenheim-Anderson-de Boer (GAB) isotherm, carrageenan is capable of absorbing up to 60% water by weight at high humidity [14], which makes it a promising material for FPI sensors.

The aim of this work is to develop and numerically verify a physical model of an IFP humidity sensor with a carrageenan coating, including a description of sorption, swelling, diffusion, Gaussian beam optics and temperature effects, as well as to search for optimal geometric parameters of the sensor using the Adam gradient algorithm [15].

Design and Operating Principle of the Sensor

Sensor Diagram. The sensor under consideration (Fig. 1) consists of a standard single-mode fiber SMF-28 (cladding diameter 125 μm), a section of bare fiber (Hollow-Core Fiber, HCF) with a length of L = 50 μm, forming an air resonator, and an end mirror represented by the surface of a polymer layer of thickness d_{coat} [9]. Light emerging from the SMF-28 core is partially reflected from the first SMF/air boundary (reflection coefficient R_1) and from the second air/polymer boundary (R_2), creating two-beam interference.

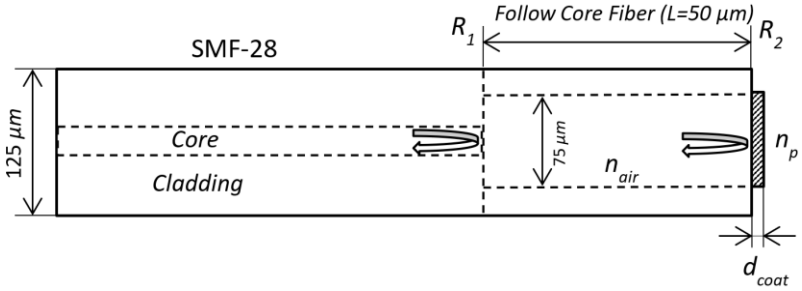


Fig. 1. Schematic diagram of a fiber-optic humidity sensor based on an IFP: SMF-28 is a single-mode fiber; HCF is a hollow gap of length L; n_{air} is the refractive index of air; n_p is the refractive index of the coating; d_{coat} is the coating thickness.

The resonant wavelength of the FPI in reflection mode is defined as:

$$\lambda_m = 2\cdot\left(n_{air}\cdot L + n_p\cdot d_{coat}\right)/m,\ m = 1,\ 2,\ 3,\ \ldots$$

where m is the interference order. When absorbing moisture, the polymer swells ($d_{coat} \rightarrow d_{coat} + \Delta d$) and changes its refractive index ($n_p \rightarrow n_p + \Delta n_p$), causing a shift in λ_m proportional to the relative humidity.

Physical Model of the Resonance Condition. The reflected signal intensity is described by the Airy formula [16] for a low-fineness interferometer ($F \ll 1$):

$$I_{out} = I_{in}\cdot A\cdot[1-(1-2R)\cdot\cos(4\pi n_{eff}\cdot L/\lambda + 4\pi\cdot n_{coating}\cdot d/\lambda)],$$

where n_{eff} is the effective refractive index of the fiber core in the gap, L is the length of the air cavity, $n_{coating}$ is the current refractive index of the coating, d is its thickness, λ is the wavelength, and A is the total amplitude loss coefficient (diffraction, absorption, scattering). The resonant wavelength λ_{res} is determined by the condition:

$$m\cdot\lambda_{res} = 2\cdot\left(n_{eff}\cdot L + n_{coating}\cdot d\right),\ .$$

When moisture is absorbed, the coating swells, increasing d, and simultaneously dilutes with water, decreasing $n_{coating}$. The total optical path $n_{coating}\,d$ increases, leading to a redshift of λ_{res}.

Accounting for Diffraction Losses. Since the Gaussian beam expands after passing through the air gap, a diffraction overlap coefficient η is introduced [16]:

$$\eta = \left[w_0 / w(2L) \right]^2,\ w(z) = w_0 \cdot \sqrt{\left[1 + \left(z / z_R \right)^2 \right]},\ z_R = \pi \cdot w_0^2 / \lambda .$$

For L = 50 μm and w_0 = 5.20 μm, we obtain $w(2L) \approx 10.82$ μm, $\eta \approx 0.610$. This coefficient is taken into account when calculating the signal-to-noise ratio (SNR) and determines the threshold for detecting resonance shift.

Moisture Sorption Model (GAB)

To describe the water absorption isotherm of carrageenan, a three-parameter GAB model was used [14, 17, 18]:

$$W(H,T) = \frac{W_m \cdot C \cdot K \cdot a_w}{\left[(1 - K \cdot a_w) \cdot (1 - K \cdot a_w + C \cdot K \cdot a_w) \right]},$$

where $a_w = H/100$ is the water activity, H is the relative humidity (%RH), W_m is the monolayer capacity, C is the Guggenheim constant, and K is the de Boer factor. The parameter values for the hybrid κ/ι-carrageenan used in the model are taken from [19] and are given in Table 1.

Table 1. Parameters of the GAB model for hybrid κ/ι-carrageenan

GAB parameter	Designation	Meaning	Description
C	C_{GAB}	10.9	Sorption constant
K	K_{GAB}	0.92	Water activity factor
W_m	W_{mono}	0.068 g/g	Monolayer capacity
W_{max}	W_{max}	0.60 g/g	Maximum water absorption

Upon reaching $W = W_{max} = 0.60$ g/g, further growth is limited, which corresponds to saturation of the hydrophilic regions of the carrageenan chain at high humidity. At T = 25°C and RH = 50%, the model yields $W \approx 0.114$ g/g.

The change in the refractive index of the coating is described by the mixture rule (Lorentz–Lorenz model):

$$n_{coating}(W,T) = n_{dry} - \alpha_{dn} \cdot W + \alpha_T \cdot (T - T_{ref}),$$

where $n_{dry} = 1.540$ is the refractive index of dry carrageenan, $\alpha_{dn} \approx 0.24$ rel. units/(g/g) is the dilution factor, and $\alpha_T \approx -9.5 \times 10^{-5}$ °C^{-1} is the thermo-optical coefficient. The swelling of the coating is described by a linear law:

$$d(W,T) = d_0 \cdot \left[1 + \beta \cdot W + \gamma \cdot (T - T_{ref}) \right],$$

where $\beta \approx 0.50$ is the volumetric swelling coefficient, and $\gamma \approx 6.5 \times 10^{-5}$ °C^{-1} is the polymer's thermal expansion coefficient. The thermal expansion of the quartz fiber is taken into account separately ($\alpha_{quartz} = 5.5 \times 10^{-7}$ °C^{-1}).

Temperature Compensation Algorithm

Temperature contributions are due to three mechanisms:

- thermal expansion of the quartz resonator (the linear temperature expansion coefficient of quartz $\alpha_{SiO_2} = 0.55$ x 10^{-6} K^{-1});
- change in the refractive index of air in the resonator ($dn_{air}/dT = -8.8$ x 10^{-7} K^{-1});
- thermomechanical expansion of the polymer layer (the linear temperature expansion coefficient of the polymer $\alpha_p \approx 200$ x 10^{-6} K^{-1}). Without compensation, the total temperature

sensitivity coefficient is ≈66.6 pm/°C, which is equivalent to an error of 31.3% RH in the range of −20…+60°C [16].

The proposed algorithm for multi-level temperature compensation is performed in three stages:

1. *Calibration measurements* at three fixed RH values (30, 50, 70%) in the temperature range of −20…+60°C with a 5°C increment. $\lambda_{ref}(H, T)$ is calculated for each pair (H, T).

2. *Approximation of the correction surface* using the least-squares method:

$$\Delta\lambda_{comp}(T) = p_0 + p_1 \cdot T + p_2 \cdot T^2.$$

3. *Correction* of the measured wavelength: $\lambda_{corr} = \lambda_{meas} - \Delta\lambda_{comp}(T)$, after which H is determined from the inverse function $\lambda_{corr}(H)|_{T=25°C}$.

After compensation, the temperature sensitivity coefficient (TSC) is reduced to 0.05–0.52 pm/°C (depending on the optimization point), the root mean square error (RMSE) for temperature is 13.9–18.1 pm, which corresponds to an error of 0.10–0.15 %RH, an improvement of 270–313 times compared to the uncompensated case.

Method of Optimizing Sensor Parameters

To find the optimal set of design parameters {L, R, λ_0, d_{coat}}, the composite objective function was minimized:

$$J(L, R, d) = w_S \cdot f_S + w_T \cdot f_T + w_L \cdot f_L,$$

where $f_S = 1 - S/S_{max}$ is the penalty for insufficient sensitivity; $f_T = RMSE_T/RMSE_{max}$ is the penalty for temperature instability; $f_L = 1 - R^2$ is the penalty for nonlinearity; weights $w_S = 0.40$, $w_T = 0.30$, $w_L = 0.30$.

Optimization was performed using the Adam method (first-order optimizer) with the following parameters [15]: learning rate $\eta = 0.01$, $\beta_1 = 0.9$, $\beta_2 = 0.999$, $\varepsilon = 10^{-8}$, and the number of iterations up to 1500. The gradient of the objective function was calculated using finite differences.

The algorithm converged at the 102nd iteration (gradient norm 5.5 x 10^{-7}, σ cost 3.4 x 10^{-15}) in 16.9 s on a standard PC. Optimal parameters: L = 50.00 μm; d_{coat} = 5.04 μm; R = 0.045; λ_0 = 1550.0 nm.

Computational cost was significantly reduced by caching results (accessing the cache every 5–10 iterations for slowly varying quantities – S and T_{stab}), which reduced the number of full FPI model calculations by approximately 30%.

Simulation Results

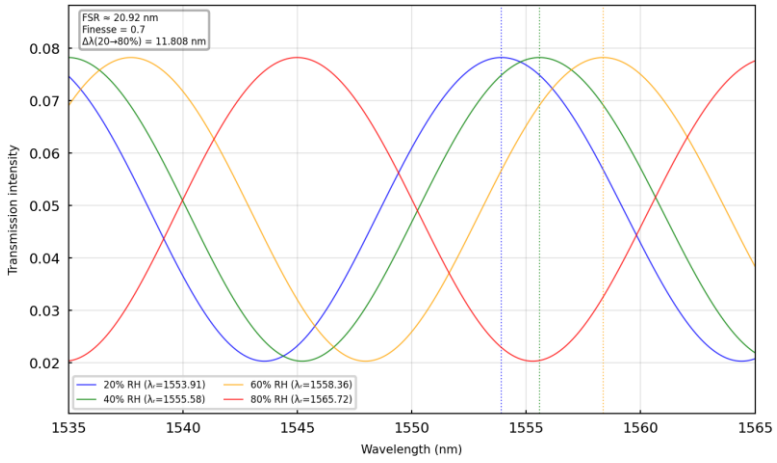


Fig. 2. Reflectance spectrum of the Fabry–Perot interferometer in the range of 1535–1565 nm at four humidity values. FSR ≈ 20.92 nm, finesse = 0.7, Δλ(20→80%) = 11.81 nm

Spectral Characteristics. Figure 2 shows an enlarged reflection spectrum of the sensor near λ_0 = 1550 nm at various relative humidity values (20–80% RH). It can be seen that the resonance shifts toward longer wavelengths with increasing humidity. The shift from 20 to 80% RH is approximately 11.8 nm, which corresponds to an average sensitivity of ≈ 197 pm/% RH in this range. The peak intensity remains virtually unchanged (~ 0.078), since the diffraction overlap coefficient $\eta \approx 0.610$ depends weakly on humidity.

Dependence of the Resonant Wavelength on Humidity and Temperature. Figure 3 shows the sensor response curves. The left graph shows the resonant wavelength as a function of humidity at T = 25°C: a nonlinear, nearly logarithmic, dependence is observed, accelerating at RH > 80%, due to the transition to capillary condensation of moisture in the polymer according to the GAB model. A linear approximation in the range of 10–95% RH yields S = 150.5 pm/% RH with R^2 = 0.9512.

The right graph in Figure 3 shows the temperature dependence at H = 50% RH: the linear TSC ≈ 66.6 pm/°C without compensation. Thanks to the compensation algorithm, the residual TSC is 0.05–0.52 pm/°C.

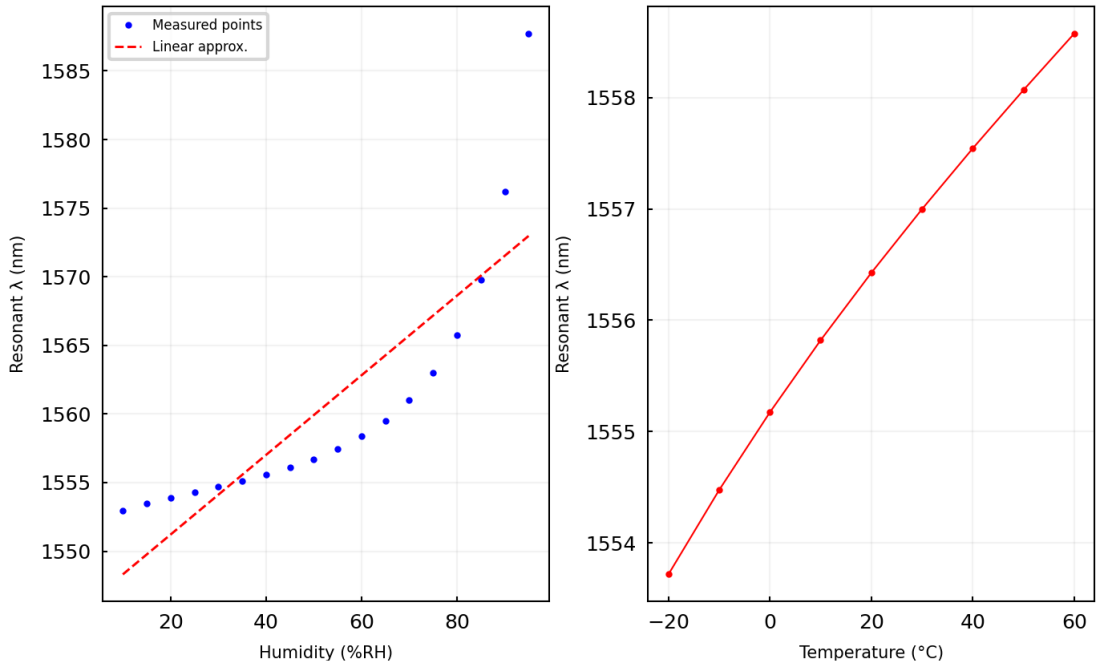


Fig. 3. Sensor characteristics: (left) dependence of the resonant wavelength on humidity at T = 25°C with a linear approximation (dashed line); (right) temperature dependence at H = 50% in the range of −20…+60 °C

Two-Dimensional $\lambda(H, T)$ Map. Figure 4 shows a two-dimensional map of the resonance wavelength as a function of humidity and temperature. The λ = const contours have a noticeable slope along the T axis, which is the source of the temperature cross-sensitivity. The λ range varies from ≈ 1550 nm (low humidity, low temperature) to ≈ 1595 nm (high humidity, high temperature), which accounts for the full resonance shift range of $\Delta\lambda \approx 45$ nm.

Response Time. Figure 5 shows the dependence of the response time on the coating thickness. The diffusion constant of carrageenan is taken to be $D = 3.0\times10^{-12}$ m²/s [18, 20]. The characteristic diffusion time is $\tau = d^2/(\pi^2 D)$, $\tau_{90} = \tau\cdot\ln(10)$. At the optimal thickness of d_{coat} = 5.04 μm: τ = 214 ms, τ_{90} = 493 ms (the "fast response" region is < 500 ms). Thus, the sensor responds to changes in humidity approximately twice as fast as typical hydrogel sensors with a coating thickness of 5–10 μm and a response time of several seconds.

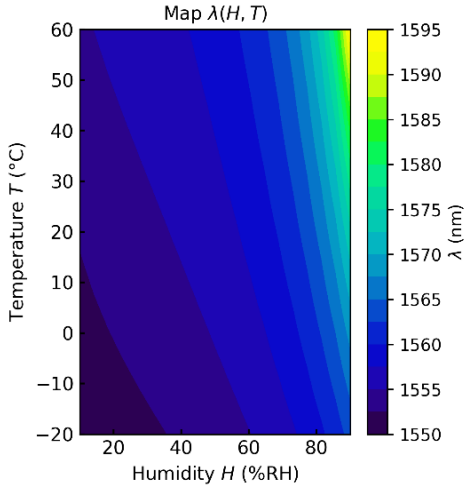


Fig. 4. Map of the resonance wavelength λ(H, T) in humidity–temperature coordinates. The color scale corresponds to the wavelength in nm.

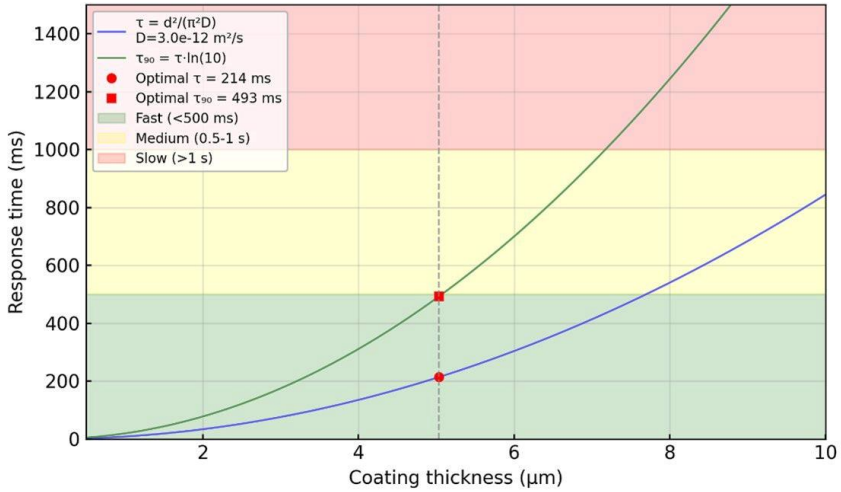


Fig. 5. Sensor response time as a function of coating thickness. Optimum point (d = 5.04 μm): τ = 214 ms, τ_{90} = 493 ms. Color zones: green – fast response (<500 ms), yellow – medium (500 ms – 1 s), red – slow (>1 s)

Summary of Optimal Parameters. Table 2 shows the results of the obtained optimal parameters and sensor characteristics.

Table 2. Optimal Parameters and Sensor Characteristics

Parameter	**Meaning**
Wavelength λ_0	1550.0 nm
Cavity length *L*	50.00 mkm
Reflectivity *R*	0.045
Coating thickness *d*	5.04 mkm
Refractive index (dry)	1.5400
neff (quartz)	1.4682
FSR	20.87 nm
Finesse	0.7
Q-factor	51
SNR	47.4 dB
Sensitivity *S*	150.5 pm/%RH

Response time τ	214 ms
Time τ_{90}	493 ms
Linearity R^2	0.9512

Discussion

Comparison with the Prototype. Table 3 compares the proposed sensor with the prototype [9] – a chitosan-based IFP sensor. Direct comparison is difficult due to the differences in materials, but it demonstrates the fundamental advantages of carrageenan as a sensing layer.

Table 3. Comparison with the prototype [9]

Parameter	Prototype [9]	Suggested sensor
Coating material	Chitosan	Carrageenan
Cavity length, μm	50	50
Coating thickness, μm	6.2	5.04
Sensitivity, pm/%RH	130.0	150.5
RH range	20–95%	10–95%
Response time τ	380 ms	214 ms

The simulated sensor outperforms the prototype in sensitivity (150.5 vs. 130.0 pm/%RH) and response time, primarily due to the high-water absorption of carrageenan (W_{max} = 0.60 g/g). The increased swelling is the primary contributor to the increased sensitivity: every 10% increase in humidity results in $a \approx 1.5$ nm shift in λ_{res}. Comparison with previously published sensors based on other hydrophilic polymers (Nafion, PVA, gelatin, etc.) shows that carrageenan provides competitive sensitivity at a significantly lower cost and better biocompatibility [5, 8, 10]. The biodegradability of carrageenan [21] opens up potential for use in environmentally friendly, disposable monitoring systems.

Analysis of Model Limitations. A number of assumptions of the adopted model should be noted. First, the GAB model provides an accuracy of describing the carrageenan sorption isotherm of ±5–8% in the range of 10–95% RH [14], but deviates at very low (<10%) and very high (>90%) humidity values. Second, the model assumes that the diffusion coefficient D is independent of moisture concentration, whereas real carrageenan exhibits a nonlinear decrease in D with swelling [20]. Third, it is assumed that the coating swelling is isotropic and uniform across the thickness, which may not be the case for thin films [19]. These factors can lead to discrepancies between the calculated and experimental values within 5–10%. The linearity of the deterministic function (R^2 = 0.9512) is satisfactory for a first-order sensor; however, a nonlinear calibration function would be required for metrology applications. This limitation is inherent in the GAB isotherm of carrageenan, which is S-shaped in nature.

Conclusion

In this study, a physical and mathematical model of a fiber-optic humidity sensor based on a Fabry-Perot interferometer with a sensitive carrageenan coating was developed and numerically optimized. Key results:

1. A multi-level physical model is proposed, including the GAB sorption isotherm, swelling equations, thermo-optical coating shifts, and Gaussian diffraction loss in the air gap.

2. Based on the optimization results (Adam, 102 iterations), the following parameters were determined: L = 50.0 μm, d = 5.04 μm, R = 0.045 at λ_0 = 1550 nm.

3. A sensitivity of S = 150.5 pm/%RH (R^2 = 0.9512) was achieved, which corresponds to the upper limit of the target range of 120–150 pm/%RH and exceeds the characteristics of the prototype based on chitosan [9].

4. The developed multi-level temperature compensation algorithm reduces the error from 31.3 %RH to 0.10–0.15 %RH (an improvement of 270–313 times) in the range of −20…+60 °C.

5. The sensor response time τ = 214 ms, τ_{90} = 493 ms – in the "fast" response zone, making it applicable for tasks with a sampling rate of up to 2 Hz.

6. SNR = 47.4 dB and Q-factor = 51 provide sufficient margin for detecting resonance shifts at the noise level of modern OSA.

The obtained modeling results provide the basis for experimental fabrication and testing of the sensor. Priority areas for further research include: deposition of a carrageenan film using dip coating or electrostatic deposition, experimental verification of the GAB isotherm, and validation of the temperature compensation algorithm under real-world conditions.

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PROPAGATION OF WAVES IN INFINITELY LONG LAYERED VISCOELASTIC CYLINDRICAL MECHANICAL BODIES

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Abstract. *The paper considers the propagation of natural waves in a thin cylindrical shell and constructs The dispersion dependence of a flexural wave in the walls of a viscoelastic cylindrical shell. The wall thickness of the cylindrical shell was assumed to be so small that all effects associated solely with its changes over time were neglected. In this approximation, the waveguide, which represents such a shell, is single-mode across the entire frequency range, with the exception of a small range in which attenuation-free propagation is impossible. For a more detailed examination of wave processes in an extended cylindrical shell, both within this frequency range and beyond, it is necessary to consider an approximation in order of smallness. From here on, it is appropriate to refer to the wave of change in the radius of the centerline of the cross-section, as a flexural wave.*

Keywords: *cylindrical shell, dispersion dependence, wave propagation, shell wall, natural wave.*

1.Introduction

The dispersion relation of a circular cylindrical shell has been a subject of great interest for several decades [1-4]. In some studies, numerical procedures were used exclusively for calculating dispersion relations. In [5], an analytical expression for the dispersion relations from Flügge shell theory was obtained using the Mathematica symbolic algebra package. Karchub's main concern was to verify the correspondence between his analytical results and those obtained previously using numerical methods, and was limited to harmonic orders. $n \geq 1$. Axisymmetric modes (n=0) are important for the transmission of longitudinal waves, and are particularly important in acoustics because of their high radiation efficiency. In order to have complete analytical solutions for the shell dispersion relations, solutions for the n=0 cases are included and discussed in this paper. Solutions to the modal models for each of the propagating and evanescent modes are also important and are not discussed in [6].

These solutions are crucial for determining the vibration of a finite shell under various allowable boundary conditions and arbitrary external forces. The dispersion relations and their associated eigenvectors also provide a means by which transmission matrices for vibroacoustic transmission in cylindrical shell structures or pipe-and-hose systems can be constructed [7–9]. A traditional and standard method for finding the eigenvectors has been described in detail in [10];

an eigenvector was normalized such that its radial displacement component was equal to unity, while the longitudinal and circumferential components were expressed as ratios of the displacement with respect to the radial displacement. In some cases these ratios could become extremely large and the eigenvector could thus deviate significantly from the eigenvector commonly used in mathematical physics [11,12]. To improve this problem of finding normalized eigenvectors with norms equal to unity, an alternative method is proposed using the built-in eigenvalue problem in any numerical package [13,14].

Continuously changing mode models for all kinds of wave types in the desired frequency range will be quickly obtained, and the physical meanings of wave propagation can also be shown more clearly and straightforwardly IN [15]. Apparently, the term "Lamb wave" is commonly used for this mode. This likely stems from the analogy of this wave with the conventional antisymmetric Lamb wave defined for a flat layer. However, in the case of waves in the wall of a cylindrical shell, this can lead to confusion, since at low frequencies, when the wavelength is commensurate with the radius of curvature, the wave in the pipe wall and the wave in the flat layer behave differently. Furthermore, the literature on pipes does not always specify the type of plane Lamb wave with which the analogy is drawn—antisymmetric or symmetric—despite the fact that these phenomena already have significant qualitative differences from their "flat" prototypes..

Problem statement and solution methods

Here we consider the problem of wave propagation in dissipatively homogeneous and inhomogeneous three-layer cylindrical bodies (without fluid). The equations of motion of the surrounding medium and the cylindrical body are as follows [16]:

$$\tilde{\mu}_n\nabla^2\vec{u} + (\tilde{\lambda}_n + \tilde{\mu}_n \quad)graddi\vartheta \quad \vec{u} = \rho_n \frac{\partial^2\vec{u}}{\partial t^2}$$

, (n =1, 2, 3…..N.) (1)

Here $\vec{u}(u_x, u_y, u_z)$ -vector of displacement of points of the environment; ρ_j - density of the material; u – displacement components; ν - Poisson's ratio;

$$.\tilde{\lambda}_n\phi(t) = \frac{\nu_n\tilde{E}_n\phi(t)}{(1+\nu_n)(1-2\nu_n)}\ ; \qquad \tilde{\mu}_n\phi(t) = \frac{\nu_n\tilde{E}_n\phi(t)}{2(1+\nu_n)}$$

In the case where the Koltunov-Rzhanitsen relaxation kernel is used in place of (1), then the elastic modulus is replaced by operators, i.e. $\tilde{E}_n$ – the operator modulus of elasticity has the form [17]:

$$(2)\tilde{E}_n\phi(t) = E_{0n}\left[\phi(t) - \int_0^t R_{En}(t-\tau)\phi(t)d\tau\right]$$

$\varphi(t)$ – an arbitrary function of time; $R_{En}(t-\tau)$ – relaxation core; E_{01} –instantaneous modulus of elasticity.

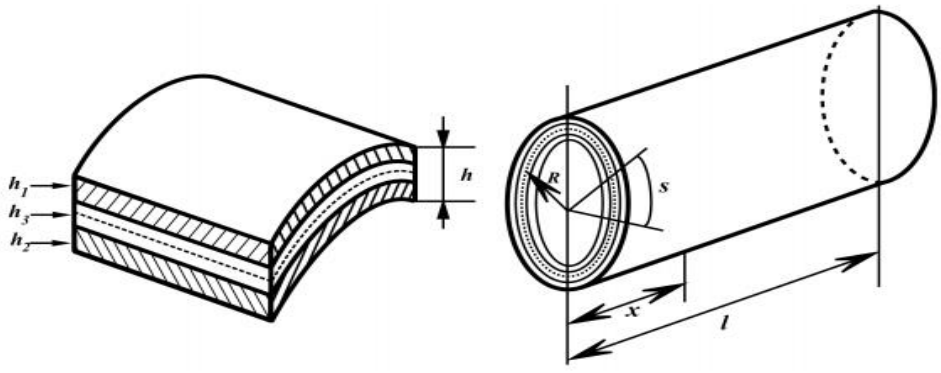


Fig. 1. Calculation scheme. Three-layer structure.(h1- first layer, h2- second layer, 3- filler).

Then the boundary conditions (internal and external boundaries are free from loads, the condition of rigid fixation at the boundary of two layers) have the following form:

$$\begin{aligned}
&r = r_1, \qquad \sigma_{rr1} = 0, \quad \sigma_{r\theta 1} = 0, \quad \sigma_{rz1} = 0,\\
&r = r_2, \qquad \sigma_{rr1} = \sigma_{rr2}, \quad \sigma_{r\theta 1} = \sigma_{r\theta 2}, \quad \sigma_{rz1} = \sigma_{rz2},\\
&\qquad\qquad u_{r1} = u_{r2}, \quad u_{\theta 1} = u_{\theta 2}, \quad u_{z1} = u_{z2},\\
&r = r_3, \qquad \sigma_{rr2} = \sigma_{rr3}, \quad \sigma_{r\theta 2} = \sigma_{r\theta 3}, \quad \sigma_{rz2} = \sigma_{rz3},\\
&\qquad\qquad u_{r2} = u_{r3}, \qquad u_{\theta 2} = u_{\theta 3}, \qquad u_{z2} = u_{z3},\\
&r = r_4, \qquad \sigma_{rr3} = 0, \qquad \sigma_{r\theta 3} = 0, \qquad \sigma_{rz3} = 0.
\end{aligned} \tag{3}$$

The displacements of the elements of a three-layer cylinder are expressed through the Bessel and Neumann functions:

$$\begin{aligned}
u_{r\kappa} &= \sum_{n=0}^{\infty} \Big\{ \gamma_\kappa \left[A_{1\kappa} J'_\kappa(\gamma_{1\kappa} r) + A_{2\kappa} Y'_\kappa(\gamma_{1\kappa} r)\right] + \frac{n}{r}\left[A_{3\kappa} J_\kappa(\gamma_{2\kappa} r) + A_{4\kappa} Y_\kappa(\gamma_{2\kappa} r)\right] - \\
&- \frac{\alpha \gamma_{2\kappa}}{\mu_{2\kappa}}\left[A_{5\kappa} J'_\kappa(\gamma_{2\kappa} r) + A_{6\kappa} Y'_\kappa(\gamma_{2j} r)\right]\Big\} \cos n\varphi e^{i(-\omega t + \gamma z)},\\
u_{\varphi\kappa} &= -\sum_{n=0}^{\infty} \frac{n}{r}\Big\{ \gamma_\kappa \left[A_{1\kappa} J_\kappa(\gamma_{1\kappa} r) + A_{2\kappa} Y_\kappa(\gamma_{1\kappa} r)\right] + \frac{r\gamma_{2\kappa}}{n}\left[A_{3r} J'_k(\gamma_{2k} r) + A_{4k} Y'_k(\gamma_{2k} r)\right] - \\
&- \frac{\alpha}{\mu_{2r}}\left[A_{5k} J_k(\gamma_{2k} r) + A_{6k} Y_k(\gamma_{2k} r)\right]\Big\} \sin n\varphi e^{i(-\omega t + \gamma z)},\\
u_{zk} &= \sum_{n=0}^{\infty} \Big\{ \gamma_k \left[A_{1k} J_k(\gamma_{1k} r) + A_{2k} \gamma_k(\gamma_{1k} r)\right] + \\
&+ \frac{\gamma_{2k}^2}{n}\left[A_{5k} J_k(\gamma_{2k} r) + A_{6k} Y_k(\gamma_{2k} r)\right]\Big\} \cos n\varphi e^{i(\omega t + \gamma z)}.
\end{aligned} \tag{4}$$

Here

$$\gamma_{1k}^2 = \bar{\mu}_{1k}^2 - \gamma^2, \quad \bar{\mu}_{1k} = \frac{\omega}{a_{1k}\Gamma_k}, \quad \gamma_{2k}^2 = \bar{\mu}_{2k}^2 - \gamma^2,$$

$$\bar{\mu}_{2k} = \omega / a_{2k}\Gamma_{2k}, \quad a_{2k}^2 = \frac{\bar{\mu}_k}{\rho_k}, \quad \gamma = m\pi / l, \ (m = 1,2,\ldots) \quad (k = 1,2,3).$$

If the displacements (4) are known, then the components of the deformations and stresses can be found. Substituting into (4) the components of the displacements and the stresses found through them, then to determine arbitrary constants $A_{1k}, A_{2k}, A_{3k}, A_{4k}, A_{5k}, A_{6k}$ we obtain a system of 18 homogeneous algebraic equations (with complex coefficients) with 18 unknowns

$$(3)[C]\{q\} = \{0\}$$

In order for a homogeneous system of algebraic equations to have non-trivial solutions, the main determinant of the system of equations must be equal to zero: ($[C]$=0), the elements of the last equations are expressed through the Bessel functions of the first and second kind of the nth

order. The order of the determinant given above is 18. When expanding this determinant, we obtain a transcendental equation with respect to the complex amplitude . This equation is solved using a specially developed algorithm (based on the Müller and Gauss methods, as well as methods for calculating the determinant of a matrix) and a program.$C_{ij}(i = 1,2,\dots,18; \quad j = 1,2,\dots,18)\omega$

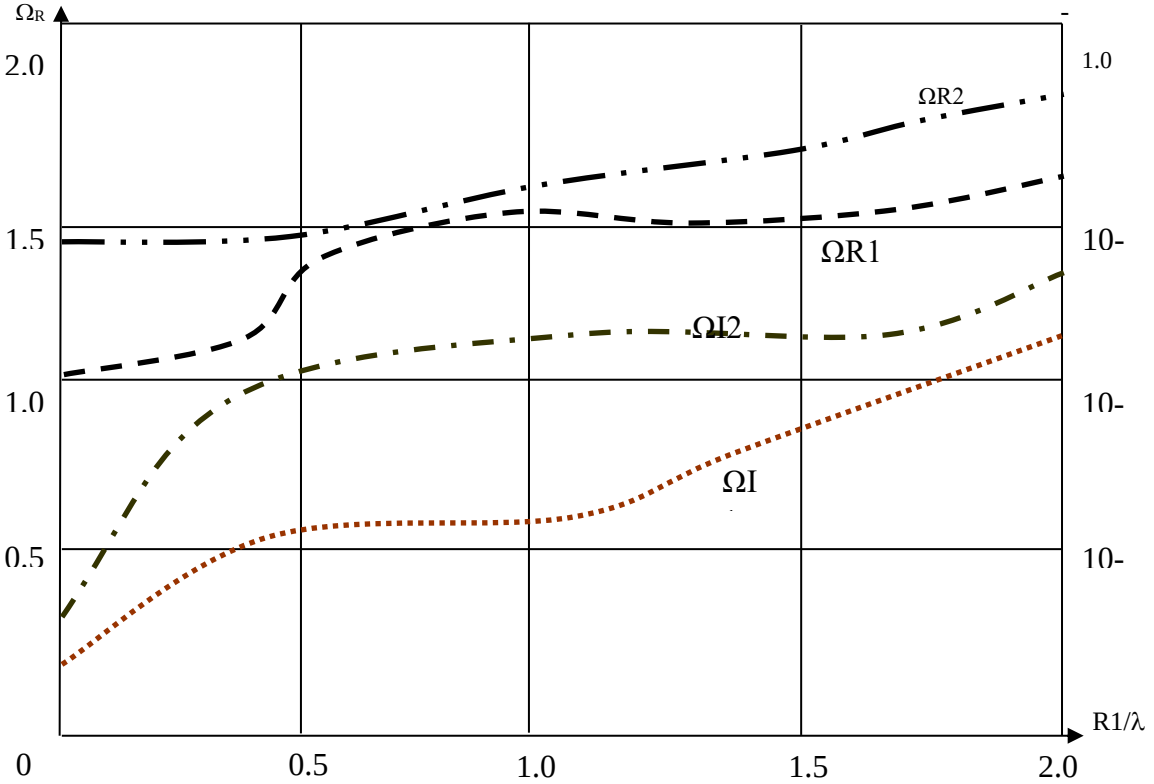


Fig. 1. Change in actual$\Omega_R$and imaginary$\Omega_I$parts of the complex frequency as a function of the wave number (dissipative homogeneous system)

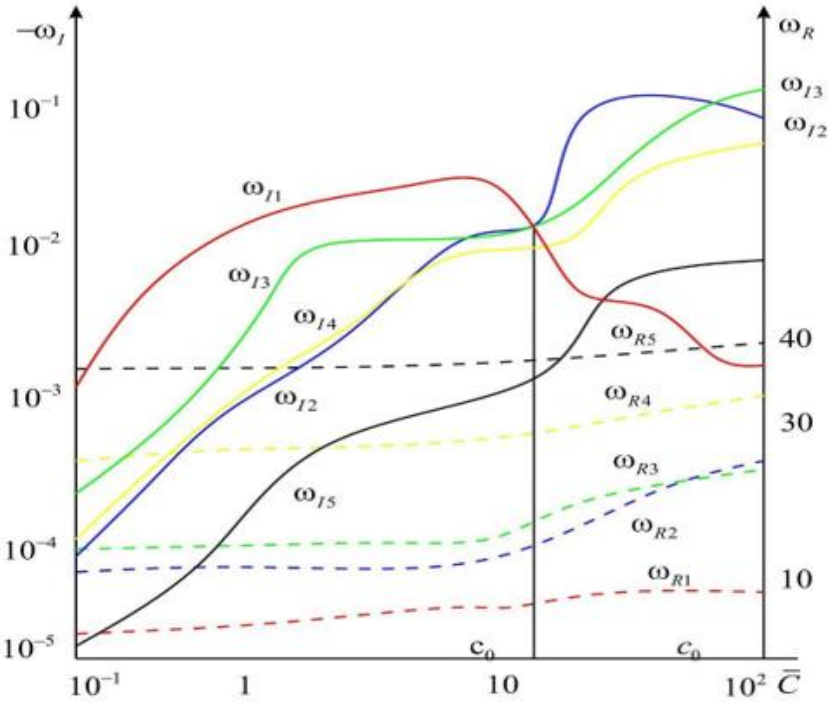


Fig. 2. Change in actualΩ_R and imaginary$\Omega_I$parts of the complex frequency as a function of the wave number (dissipative-inhomogeneous system)

In all the cases considered, the following were adopted: Poisson's ratio of the midsurface is 0.25; the density ratio is:ρ_{With}/ρ=0.35 (the ratio of the density of the middle surface to the density of the outer layer); Gc/μ- the ratio of the bulk compression modulus to the shear modulus of the outer layer is 0.20; μ_{With}/μ- the ratio of the shear modulus of the middle surface to the shear modulus of the outer layer is equal to 0.11(1+Γκ), $\Gamma_{\kappa} = 1 - \Gamma^{C}(\omega_R) - i\Gamma^{S}(\omega)$. The calculation results (changes in the real and imaginary parts of the complex frequency as a function of the wave number) are shown in Fig. 2 and Fig. 3 (h/b=0.1) for dissipative-homogeneous and inhomogeneous systems. The effect of expressing the change in the attenuation coefficient as a function of the wave number through monotonic functions (at values of maximum convergence of the real parts of the frequencies or phase velocity) is confirmed. New branches of this effect are revealed. The imaginary parts of the first, second, and third frequencies act as the global attenuation coefficient for dissipative-inhomogeneous systems. This opens up new possibilities for optimizing the dissipative properties of a mechanical system.

Conclusions

1. To characterize the dissipative properties of a mechanical system, the parameter δ (the global damping coefficient (GDC)) was introduced. For dissipatively homogeneous systems, the absolute value of δ is determined by the imaginary part of the first complex frequency. For dissipatively inhomogeneous mechanical systems, the role of δ is played by the imaginary parts of the first, second, third, etc. frequencies.

2. It has been established that the group velocity in a non-dispersible medium will be 16% greater than the group velocity of a dispersible medium.

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STUDY OF REFERENCE SOLAR CELLS PREPARED FOR MEASURING SOLAR IRRADIATION INTENSITY

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Abstract. *In this work, silicon solar cells of different sizes were tested by measuring the intensity of solar radiation in the conditions of the city of Termez. The results obtained from the reference solar elements were compared with the values measured using the measuring instrument "CEM DT-1307 Solar Power Meter" manufactured at the factory. The results of the study showed that the indicators of both measuring instruments do not differ significantly from each other.*

Keywords: *monocrystalline, reference solar cells, solar radiation intensity, short-circuit current, ammeter, geographical latitude, solar energy.*

Introduction

Solar energy measurement is important in the use of solar devices. To ensure the accuracy and reliability of the measuring instruments, they are checked and calibrated at regular intervals. Solar measuring instruments require accurate measurement of high-intensity solar radiation. Typically, the solar radiation intensity exceeds 1000 W/m^2. Modern measuring instruments are aimed at achieving even higher temperatures and irradiance levels as part of the 3rd generation program of the Solar Energy Technologies Office (SETO) of the Department of Energy [1-2]. Vacuum-type solar energy measuring instruments are very accurate measuring instruments suitable for measuring high-intensity radiation over a wide radiation spectrum. The vacuum radiometer, developed by J.M. Kendall, is an absolute measuring instrument that can measure from the far ultraviolet to the far infrared [3]. In addition, circular film meters, called Gardon meters [4], and axial thermoplastic film sensors, called Schmidt-Boelter meters, are inexpensive, robust, and reliable radiation measuring devices, and are also widely used for high-intensity radiation measurements [5].

Methods and materials

In the experimental work, monocrystalline silicon solar cells with dimensions of 4cm x 4cm and 6cm x 2cm were used. (Figure 1). The experimental work was carried out on September 30, 2025 in the conditions of the city of Termez (Latitude 37°13′). The relative humidity of the air was ~16%, the average wind speed was ~1.4m/s, and the atmospheric pressure was 762 mmHg The measurements were carried out from 9:00 to 15:00, with a time interval of 20 minutes. In the experiment, the short-circuit current of the reference solar cells was measured in the sun-observing mode. In the experimental work, the solar radiation intensity was measured using the "CEM DT-1307 Solar Power Meter" measuring instrument and reference solar cells. The measurement results can be seen in the table below.

Comparison table of solar radiation intensity measured using the CEM DT-1307 Solar Power Meter and reference solar cells

h:min.	E_{SPM} *(W/m^2)*	I_{SC1} *(mA)*	K_1 *(W/m^2·mA)*	I_{SC2} *(mA)*	K_2 *(W/m^2·mA)*
9:00	653	24	27,2	17,3	37,7

9:20	705	26,4	26,7	18,55	38
9:40	757	28,2	26,8	20,1	37,6
10:00	802	29,9	26,82	21,2	37,8
10:20	856	31,5	27,1	22	38,9
10:40	859	31,6	27,1	22,2	38,6
11:00	870	31,9	27,2	22,4	38,8
11:20	875	32,3	27	22,8	38,3
11:40	894	33	27	23,2	38,5
12:00	930	34	27,3	24,1	38,6
12:20	906	33,6	26,9	23,4	38,7
12:40	908	33,3	27,2	23,3	38,9
13:00	899	33,2	27	23,2	38,7
13:20	893	33	27	23,0	38,8
13:40	873	32,3	27	22,8	38,2
14:00	859	31,7	27	22,4	38,3
14:20	827	30,1	27,5	21,5	38,5
14:40	812	29,7	27,3	21,2	38,3
15:00	722	26,15	27,6	19,1	37,8
		Average value	27,1	Average value	38,3

The main purpose of the measurements is to justify the possibility of using reference solar cells made from local materials instead of measuring instruments such as the “CEM DT-1307 Solar Power Meter”, which are expensive in price and transportation costs. For this, reference solar cells made by hand at the Laboratory of Semiconductor Physics of Termez State University were used. The table above shows the ratio of the values measured by the “CEM DT-1307 Solar Power Meter” measuring instrument and the reference solar cell, K, and is expressed by the following equation:

$$K = \frac{E_{SPM}}{I_{SC}} \qquad (1)$$

where, E_{SPM} is the solar radiation intensity measured by the “CEM DT-1307 Solar Power Meter” measuring instrument, I_{SC} is the short-circuit current corresponding to the solar radiation intensity measured at the reference solar cell.

Results and Discussion

The value of the coefficient *K* determined in the experiment has a specific value for each reference solar cell and is used in subsequent measurements. To determine the intensity of solar radiation in real conditions using the reference solar cell, it is necessary to multiply the value of the short-circuit current generated by the solar cell under these conditions by the coefficient *K*:

$$E = K \cdot I_{sc} \qquad (2)$$

The data in the table above confirm that the values for the reference reference solar cells prepared in the research work are equal to K_1=27,1 $W/m^2 \cdot mA$ va K_1=27,1 $W/m^2 \cdot mA$.

In real conditions, the results obtained from the “CEM DT-1307 Solar Power Meter” device and the reference solar cells change proportionally, as can be seen in Figure 2.



Figure 1. Experimental device (Front and back)

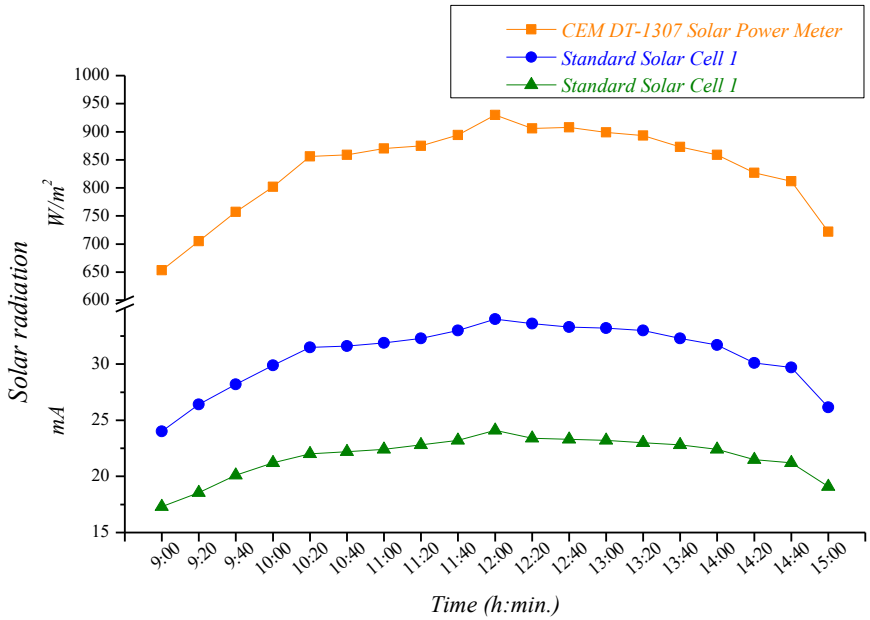


Figure 2. Dependence of solar radiation intensity on time of day obtained from the "CEM DT-1307 Solar Power Meter" instrument and reference solar cells

During the experiment, the "CEM DT-1307 Solar Power Meter" measuring instrument and the reference solar cells were kept in the shade to prevent overheating when not being measured. Calculations show that the reference solar cells prepared as part of the research are 10 times cheaper in price than measuring instruments such as the "CEM DT-1307 Solar Power Meter".

Conclusion

In conclusion, it can be noted that in any conditions, instead of expensive and expensive measuring instruments for measuring solar radiation intensity, it is possible to use reference solar cells made from local materials. The results of experiments conducted in real conditions confirm that the values obtained from these instruments are proportional to each other. Therefore, in the study, the coefficient *K* was determined, which is the ratio of the values obtained from the "CEM DT-1307 Solar Power Meter" instrument and the reference solar cells for continuous measurements.

This study was conducted on a not very hot day in September. Conducting experiments such as the above for hot summer days and anomalous cold winter days will further increase the reliability of using the prepared reference solar cells. For this, experiments should be conducted in other seasons and for other regions.

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FUZZY LOGIC-BASED LONG SHORT-TERM MEMORY NEURAL NETWORK ARCHITECTURES FOR FINANCIAL TIME SERIES FORECASTING

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Abstract. *Forecasting financial time series remains a challenging task due to high volatility, nonlinear relationships, and the presence of noise in market data. Traditional statistical approaches often struggle to capture these complex patterns, while deep learning methods have demonstrated promising results in modelling sequential dependencies. In this study, we investigate a neural network architecture that combines Long Short-Term Memory (LSTM) networks with principles of fuzzy logic for financial time series forecasting. The proposed approach introduces fuzzy logic both at the data preprocessing stage and within the neural network itself. During preprocessing, fuzzification of input data is used to represent financial observations as fuzzy sets, allowing the model to better handle uncertainty and reduce sensitivity to noise. In addition, fuzzy concepts are incorporated into the network through modified activation functions, which can be interpreted as membership functions of fuzzy sets. This design enables the model to perform operations analogous to fuzzy inference while learning temporal dependencies in the data. Experimental results on financial datasets demonstrate that the proposed fuzzy-enhanced LSTM architecture improves forecasting accuracy compared with a standard LSTM model. The findings suggest that integrating fuzzy logic with recurrent neural networks provides a promising direction for improving financial time series prediction.*

Keywords: *financial time series forecasting, Long Short-Term Memory, Fuzzy logic, Activation functions, Recurrent neural networks.*

Introduction

Financial time series forecasting represents a fundamental problem in economics and finance. Accurate predictions of financial dynamics are essential for a wide range of applications, including algorithmic trading, portfolio management, risk assessment, and macroeconomic analysis. Despite its practical importance, forecasting financial time series remains a challenging task. This difficulty arises from several intrinsic characteristics of financial data, such as non-stationarity, nonlinear relationships between variables, and the presence of significant noise in market observations (Shiryaev, 2016).

Traditional statistical approaches, including models such as ARIMA and GARCH, have been widely used to analyse and predict financial time series. While these models provide a well-established theoretical framework, their ability to capture complex nonlinear structures and rapidly changing market dynamics is often limited (Andersen et al., 2009). In recent years, deep learning techniques have gained substantial attention in the field of financial forecasting. In particular, recurrent neural networks (RNNs) and their more advanced variants, such as Long Short-Term Memory (LSTM) networks, have demonstrated strong performance in modelling sequential data and learning long-term temporal dependencies (Sezer et al., 2020). These architectures are

especially well suited for time series analysis due to their capacity to retain information from previous observations.

Nevertheless, conventional LSTM models also exhibit several limitations. In particular, they tend to be sensitive to noise in financial datasets and typically rely on fixed activation functions, which restricts their ability to adapt to the specific characteristics of different financial time series. In this study, we propose the application of fuzzy logic to enhance financial time series forecasting. Fuzzy logic enables flexible data processing by accounting for uncertainty and variability inherent in financial markets. This approach can be integrated into neural network models at several stages.

First, fuzzy logic can be applied during the preprocessing stage through the fuzzification of input data. In this process, numerical observations are transformed into fuzzy sets, which helps to smooth noisy fluctuations and represent uncertainty more effectively. Several approaches to modelling fuzzy time series have been proposed in the literature, including representations based on linguistic variables, fuzziness distributed over time, and fuzziness distributed across the value domain (Afanasyeva et al., 2014). In addition, Hesitant Fuzzy Sets (HFS) have been used for forecasting tasks, such as predicting university admission scores in Alabama and modelling stock prices of Indian companies (Bisht & Kumar, 2016).

Another way to incorporate fuzzy logic into neural networks is through the use of fuzzy activation functions. By modifying the slope and shift parameters of activation functions, it becomes possible to adapt the behaviour of the network to the characteristics of a specific time series. In our previous work, we demonstrated that activation functions such as cloglog and loglog, which can be interpreted as transformations of the sigmoid function, may improve forecasting performance (Kumskov et al., 2025). Recent studies have also explored parametric and fuzzy activation functions as a means of improving the performance of deep neural networks (Bingham & Miikkulainen, 2022; Beke & Kumbasar, 2019).

The main objective of this study is to investigate recurrent neural network architectures with memory that incorporate principles of fuzzy logic in order to improve the accuracy of financial time series forecasting. The remainder of the paper is organised as follows. Section 2 reviews related research on financial time series forecasting, including traditional statistical approaches, neural network models, and hybrid fuzzy–neural systems. Section 3 presents the theoretical background relevant to this study, including the principles of fuzzy logic and the main characteristics of financial time series. Section 4 formulates the problem statement. Section 5 describes the architecture and operation of LSTM networks. Section 6 presents the proposed model together with the results of computational experiments and their analysis. Finally, the Conclusion summarises the main findings and outlines potential directions for future research.

Related work

Financial time series forecasting has been widely investigated using a variety of approaches, including statistical methods, machine learning techniques, and hybrid intelligent models (Praveen et al., 2025). Traditional statistical models, such as ARIMA and GARCH, have long been applied to analyse financial data and model temporal dependencies. These methods are effective in capturing linear relationships in time series; however, they often struggle to adequately represent the nonlinear and highly volatile nature of financial markets (Andersen et al., 2009; Shiryaev, 2016). Consequently, more flexible and adaptive forecasting models have attracted increasing attention in recent years.

Artificial neural networks (ANNs) have become one of the most widely used tools for financial time series prediction (Sezer et al., 2020). Architectures such as feedforward neural networks (FFNNs) and recurrent neural networks (RNNs) have demonstrated promising results in modelling complex temporal patterns (Du et al., 2021). In particular, advanced recurrent architectures including Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) networks are capable of learning long-term dependencies in sequential data (Hewamalage et al., 2021). Nevertheless, the performance of neural network models strongly depends on appropriate parameter tuning, feature representation, and preprocessing techniques. Furthermore, conventional neural networks often remain sensitive to noise and sudden fluctuations in financial data.

To address uncertainty and improve the interpretability of forecasting models, fuzzy logic has been incorporated into time series analysis. Fuzzy-based approaches allow the modelling of vague and imprecise information that commonly occurs in financial datasets (Orang et al., 2023). Recent studies have proposed hybrid models that combine fuzzy clustering with optimisation techniques, such as Grey Wolf Optimisation (GWO) and the Sine–Cosine Algorithm (SCA), to optimise Markov weights and improve the modelling of fuzzy relationships within time series (Yang et al., 2017).

The combination of fuzzy logic and neural networks has led to the development of neuro–fuzzy systems, which integrate the interpretability of fuzzy inference with the learning capabilities of neural networks (Kan et al., 2024). One of the earliest and most well-known frameworks of this type is the Adaptive Neuro-Fuzzy Inference System (ANFIS) (Wei, 2016).

More recent research has also focused on improving neural network adaptability through the use of fuzzy and parametric activation functions (Bingham & Miikkulainen, 2022; Beke & Kumbasar, 2019). In our previous work, we demonstrated that activation functions derived from transformations of the sigmoid function, such as the cloglog and loglog functions, can improve the predictive performance of LSTM-based forecasting models (Kumskov et al., 2025). Building upon these findings, the model proposed in the present study integrates fuzzy logic both at the data preprocessing stage and within the neural network architecture, combining input fuzzification with adaptive fuzzy activation mechanisms in the LSTM framework.

Basic Definitions and Notation

Financial Time Series

Definition 1. Time series. A time series X is defined as a sequence of chronologically ordered real-valued vectors:

$$X = \big(x(t_1), x(t_2), \dots, x(t_n)\big), x(t_i) \in \mathbb{R}^m$$

The number n is denoted as $|X|$ and represents the length of the series. A constant time step is referred to as a tick: $\Delta t = t_i - t_{i-1}$

Definition 2. Financial time series.Financial time series exhibit several distinctive characteristics. In particular, the formation of financial indices and asset prices is typically nonlinear and demonstrates temporal dependence, meaning that many financial variables retain information about past observations (Shiryaev, 2016).

Financial Time Series Forecasting Tasks

Financial time series forecasting tasks can generally be divided into two main categories depending on the expected output of the model (Sezer et al., 2020). Price forecasting refers to predicting the numerical value of an asset at a future point in time or over a specified forecasting

horizon. Trend forecasting focuses on predicting the direction of price movement rather than the exact value. This task can be formulated as a classification problem:

- Two-class problem – predicting whether the trend will be upward or downward.
- Three-class problem – predicting whether the trend will be upward, downward, or sideways.

The input data used for forecasting financial time series may originate from several sources:

- Historical prices.Past price observations and trading data collected over previous time periods.
- Fundamental analysis. Analytical methods used to estimate the intrinsic or fair value of an asset and to assess potential changes in market demand.
- Technical analysis. The study of price charts and historical trading patterns in order to identify signals that may indicate future price movements.
- Textual information. Information extracted from financial news, social media posts, and online discussions. Sentiment analysis techniques are often used to evaluate market opinions and predict investor behaviour.

Fuzzy Logic

Definition 3. Fuzzy set. A fuzzy set is defined as a pair (U, m) , where U denotes the universe of discourse and $m: U \to [0,1]$ is the membership function. For each $x \in U$ the value $m(x)$ represents the degree of membership of the element x in the fuzzy set (U, m)

In the context of this study, x corresponds to an observed value of a financial time series (for example, the price of an asset at time t_i), while U denotes the range of possible price values. For a finite universe $U = \{x_1, \cdots, x_n\}$, a , a fuzzy set (U, m) can be represented as

$$\{m(x_1)/x_1, \ldots, m(x_n)/x_n\}$$

Let $x \in U$. Then the membership function satisfies

$$m(x) = \begin{cases} 0, x\ does\ not\ belong\ to\ the\ fuzzy\ set \\ 1, x\ fully\ belongs\ to\ the\ fuzzy\ set \\ 0 < m(x) < 1, x\ partially\ belongs\ to\ the\ fuzzy\ set \end{cases}$$

Operations on Fuzzy Sets. The basic operations on fuzzy sets are defined as follows. The intersection of two fuzzy sets (fuzzy "AND") is given by $m_{A\cap B}(x) = min\left(m_{A(x)}, m_{B(x)}\right)$. The union of two fuzzy sets (fuzzy "OR") is defined as $m_A(x) = max(m_A(x), m_B(x))$

Variables. To formally describe fuzzy sets, the notions of fuzzy variables and linguistic variables are introduced. Definition 4. Fuzzy variable. A fuzzy variable is defined by the triplet $(\boldsymbol{N}, \boldsymbol{U}, \boldsymbol{A})$, where: $\boldsymbol{N}$ is the name of the variable, $\boldsymbol{U}$ is the universe of discourse, $\boldsymbol{A}$ is a fuzzy set defined on $\boldsymbol{U}$. The values of a linguistic variable can themselves be fuzzy variables. Therefore, a linguistic variable represents a higher-level abstraction. Each linguistic variable consists of the following components: a name; a set of values, also referred to as the base term set $\boldsymbol{T}$; the universe of discourse $\boldsymbol{U}$; a syntactic rule $\boldsymbol{G}$ for generating new linguistic terms using natural or formal language constructs; a semantic rule $\boldsymbol{P}$ that assigns to each value of the linguistic variable a corresponding fuzzy subset of $\boldsymbol{U}$

Membership Functions. Membership functions are used to describe the degree to which an element belongs to a fuzzy set. A variety of functional forms can be used to represent membership functions. Among them, the most commonly applied are triangular, trapezoidal, and Gaussian membership functions (see Table 1). In addition to these classical forms, certain

activation functions whose values lie within the interval $[\mathbf{0}, \mathbf{1}]$ can also be interpreted as membership functions. Examples include S-shaped functions such as $\boldsymbol{sigmoid}, \boldsymbol{cloglog}$, and $\boldsymbol{loglog}$, as well as their modified variants with shifted centres or adjusted slopes.

Table 1.Types of membership functions.

Type	Parameters	Formula
Triangular	(a, b, c)	$m(x) = \begin{cases} 1 - \frac{b-x}{b-a}, & a \le x \le b, \\ 1 - \frac{x-b}{c-b}, & b \le x \le c \\ 0, & otherwise \end{cases}$
Trapezoidal	(a, b, c, d)	$m(x) = \begin{cases} 1 - \frac{b-x}{b-a}, & a \le x \le b, \\ 1, & b \le x \le c \\ 1 - \frac{x-c}{d-c}, & c \le x \le d \\ 0, & otherwise \end{cases}$
Gaussian	(c, σ)	$m(x) = \exp\left(-\left(\frac{x-c}{\sigma}\right)^2\right)$
Sigmoid	(α, β)	$\mathrm{m(x)} = \frac{1}{1 + \exp(-\alpha(x - \beta))}$
Cloglog	(α, β)	$m(x) = 1 - exp(-exp(\alpha(x - \beta)))$
Loglog	(α, β)	$m(x) = exp(-exp(-\alpha(x - \beta)))$

Figure 1 illustrates an example of a linguistic variable called “Stock price”. The corresponding fuzzy variables are “low”, “moderate”, and “high”. The universe of discourse is defined within a specific range of possible price values.

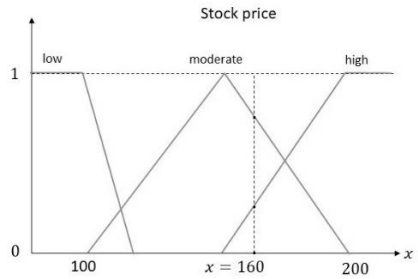


Figure 1. *Example of the linguistic variable “Stock price”. The fuzzy variables are low, moderate, and high. The universe of discourse is defined as U=[100,200]. The membership degree of the value 160 is 0 for the set low, 0.75 for the set moderate, and 0.40 for the set high.*

Fuzzy Inference. Fuzzy inference is based on a *rule base* that contains fuzzy rules together with membership functions corresponding to linguistic terms. The inference process typically consists of four stages: fuzzification, fuzzy inference, composition, and defuzzification (see Fig. 2). Different fuzzy inference algorithms mainly differ in the structure of the rule base, the logical operations applied, and the defuzzification method used (Rutkovskaya et al., 2006).

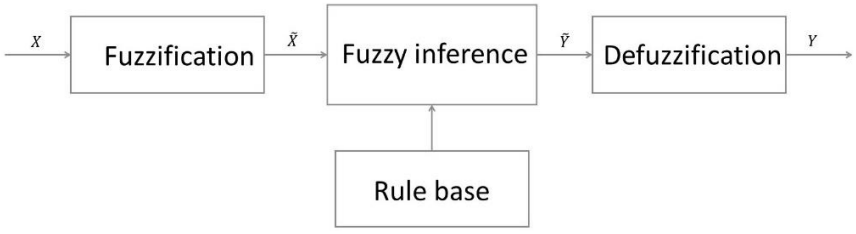


Figure 2. *Fuzzy inference mechanism. Crisp input data X are first fuzzified, producing fuzzy input values $\tilde{X}$. Fuzzy inference is then performed using a predefined rule base. The resulting fuzzy output $\tilde{Y}$. Is subsequently defuzzified to obtain the final crisp output Y.*

Problem Statement

Let us consider a one-dimensional financial time series of asset prices observed at discrete time moments. The time series can be represented as a sequence of values where the observations are recorded at a constant time interval (tick) $\boldsymbol{\Delta t} \in \{\boldsymbol{minute}, \boldsymbol{hour}, \boldsymbol{day}\}$

$$\boldsymbol{X} = (\boldsymbol{x}(\boldsymbol{t_1}), \boldsymbol{x}(\boldsymbol{t_2}), \ldots, \boldsymbol{x}(\boldsymbol{t_n})), \qquad \boldsymbol{x}(\boldsymbol{t_i}) \in \mathbb{R}$$

The forecasting task consists in predicting future values of the time series k ticks ahead, which can be written as $\boldsymbol{Y} = (\boldsymbol{y}(\boldsymbol{t_{n+1}}), \boldsymbol{y}(\boldsymbol{t_{n+2}}), \ldots, \boldsymbol{y}(\boldsymbol{t_{n+k}})$. The general structure of the proposed forecasting model follows the scheme of fuzzy inference (see Fig. 3). In the proposed approach, fuzzy inference is implemented using a neural network with modified activation functions. In this framework, activation functions are interpreted as membership functions, allowing the network to operate on fuzzy representations of the input data.

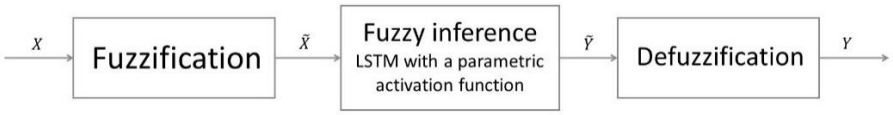


Figure 3. *General scheme of the proposed model. Crisp input data X are first fuzzified, producing fuzzy input values $\tilde{X}$. Fuzzy inference is then performed using a predefined rule base. The resulting fuzzy output $\tilde{Y}$. Is subsequently defuzzified to obtain the final crisp output Y.*

Fuzzification

There are several approaches to introducing fuzziness into financial time series data.

Gaussian Fuzzification. One possible approach is to associate each observation of the time series with a fuzzy set defined by a Gaussian membership function (see Fig. 4). In this representation, the original time series values are treated as the centres of Gaussian membership functions. For each time moment $\boldsymbol{t_i}$, the observed value $\boldsymbol{x_i}$ is associated with a fuzzy set whose membership function is defined as follows:

$$\boldsymbol{m_i}(\boldsymbol{x}) = \boldsymbol{exp}\left(-\frac{(\boldsymbol{x} - \boldsymbol{x_i})^2}{\boldsymbol{2\sigma_{i-1}^2}}\right)$$

The parameter $\boldsymbol{\sigma_{i-1}}$ represents the local volatility, which is estimated over the previous observations within the window $[\boldsymbol{t_{i-l}}, \boldsymbol{t_{i-1}}]$. Using the shifted volatility $\boldsymbol{\sigma_{i-1}}$ ensures causal fuzzification, meaning that the uncertainty at time $\boldsymbol{t_i}$ depends only on information available from previous observations.

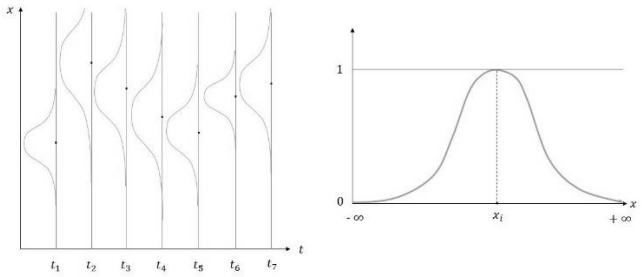


Figure 4. *Example of Gaussian fuzzification of a time series. The black dots represent the observed values x_i, while the Gaussian curves correspond to fuzzy sets associated with each time point t_i*

Additionally, an auxiliary feature is introduced:

$$\boldsymbol{m_i(x_{i-1}) = exp(-\frac{(x_{i-1} - x_i)^2}{2\sigma_{i-1}^2})}$$

This value represents the degree of membership of the previous observation $\boldsymbol{x_{i-1}}$ to the fuzzy set centred at the current value $\boldsymbol{x_i}$. As a result, the fuzzy representation of the time series contains two input channels: the normalised price value (the centre of the Gaussian set) and the membership degree $\boldsymbol{m_i(x_{i-1})}$.

Probabilistic Fuzzy Sets. Another approach to fuzzification is based on probabilistic fuzzy sets (Gupta & Kumar, 2018). The procedure consists of the following steps:

1. Define the universe of discourse $\boldsymbol{U = [X_{min} - \sigma, X_{max} + \sigma]}$ where $\boldsymbol{X_{min}}$ and $\boldsymbol{X_{max}}$ denote the minimum and maximum values of the time series within the observation window, and $\boldsymbol{\sigma}$ represents the variance.
2. Partition the universe $\boldsymbol{U}$ into $\boldsymbol{n}$ equal intervals $\boldsymbol{e_i}$
3. Construct fuzzy sets $\boldsymbol{F_i}$ over these intervals using triangular membership functions (see Fig. 5).

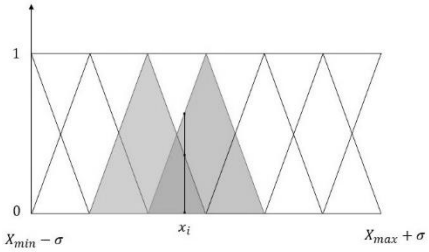


Figure 5. *Construction of probabilistic fuzzy sets. The universe of discourse U is divided into intervals e_i, and fuzzy sets F_i are defined over these intervals using triangular membership functions.*

Linguistic Variables. An alternative approach is to reformulate the forecasting task as a classification problem. In this case, the model predicts categories such as the price level, trend direction, or even the sentiment of market participants. For this formulation, fuzzy sets are defined for the corresponding linguistic variables using triangular or trapezoidal membership functions. An example of such a representation is shown in Fig. 1.

Fuzziness and Activation Functions

Let ϕ_θ denote an activation function parameterised by a set of parameters θ that determine its shape, such as the centre and slope of the function. The objective is to determine the optimal parameters θ^* of the activation function that minimise the forecasting error of the financial time series.

$$\theta^* = arg\,min_\theta\, \mathcal{L}(X, y, \theta)$$

Where $\mathcal{L}(X, y, \theta)$ denotes the loss function measuring the discrepancy between the predicted and observed values of the time series. The parameters θ include both the internal parameters of the neural network and the parameters governing the shape of the activation functions. As discussed earlier, S-shaped activation functions such as the sigmoid function and its variants with shifted centres or modified slopes can be interpreted as membership functions of fuzzy sets. Since a neural network consists of layers of neurons performing transformations through activation functions, it can be viewed as a composition of fuzzy transformations. In this interpretation, the network operates on fuzzy representations of the input data, and therefore can be regarded as a computational model of fuzzy inference.

Defuzzification.

The fuzzy outputs produced by the neural network must be converted into crisp numerical forecasts. This process is known as defuzzification.

Gaussian-Based Defuzzification. In the Gaussian fuzzification framework, the model produces a predicted value $\hat{x}_{i+1}$ at time t_{i+1}. The final crisp forecast is obtained by combining this predicted value with the previous centre of fuzzy set x_i using the membership degree m_i.

$$y_{i+1} = \hat{m}_{i+1}\, x_i + (1 - \hat{m}_{i+1})\hat{x}_{i+1}$$

This adaptive defuzzification mechanism acts as a smoothing operator, increasing the stability of the resulting forecast, particularly for highly volatile financial time series.

Probabilistic Fuzzy Sets. In the case of probabilistic fuzzy sets, triangular membership functions are defined over the partitioned universe of discourse. Given the predicted degrees of membership for each fuzzy set, a unique crisp forecast can be obtained by aggregating these membership values and computing the corresponding numerical estimate.

Linguistic Variables. When the forecasting task is formulated in terms of linguistic variables (for example, price levels such as low, moderate, or high), defuzzification is performed in an analogous manner by converting the predicted fuzzy output into a single crisp value.

Long Short-Term Memory architecture

A recurrent neural network (RNN) consists of repeating computational modules connected in a sequential chain. In this work, we employ the Long Short-Term Memory (LSTM) architecture, which represents a specialised type of RNN designed to capture long-term dependencies in sequential data. The unrolled structure of the LSTM network used in the proposed model is illustrated in Fig. 6.

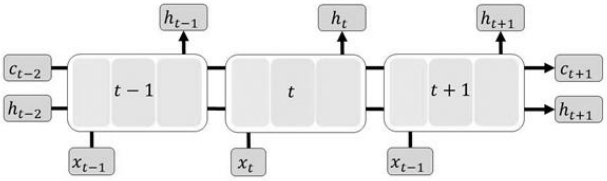


Figure 6. *Unrolled structure of the LSTM network used in the proposed model. The sequence of recurrent cells performs the fuzzy inference stage, where fuzzified financial time series data are sequentially processed by LSTM units with parametric activation functions before the defuzzification step.*

Long Short-Term Memory (LSTM) networks extend classical recurrent neural networks by introducing memory cells and gating mechanisms that regulate the flow of information through the network. Unlike standard RNN units, an LSTM module contains four interacting components, which allow the model to selectively retain or discard information (see Fig. 7).

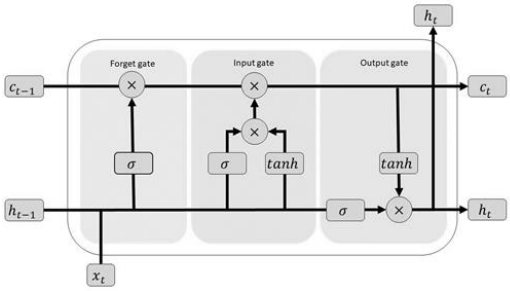


Figure 7. *Architecture of an LSTM cell. Each line represents the transfer of a vector from the output of one node to the input of another. Merging lines indicate concatenation, while*

branching arrows denote data duplication across multiple components of the network. The notation is as follows:c_t – cell state, x_t – input vector,h_t – output (hidden state), $\times$ – elementwise multiplication, $+$ – vector addition, σ – sigmoid layer, and $\tanh$ — hyperbolic tangent layer.

This architecture enables efficient modelling of long-term dependencies in sequential data, allowing the network to recognise patterns over extended time intervals, identify events separated by long time gaps, and extract temporal relationships embedded in the data (Hochreiter & Schmidhuber, 1997).

At each time step $\boldsymbol{t}$, the LSTM module receives the input vector $\boldsymbol{x_t}$ together with the previous hidden state $\boldsymbol{h_{t-1}}$. The behaviour of a standard LSTM cell can be described by the following system of equations, where $\boldsymbol{W}$. denote weight matrices and and $\boldsymbol{b}$. denote bias vectors.

Forget Gate. $\boldsymbol{f_t = \sigma_f(W_f\,[h_{t-1}, x_t] + b_f)}$ The forget gate determines which information from the previous cell state should be retained.

Input Gate $\boldsymbol{i_t = \sigma_i(W_i\,[h_{t-1}, x_t] + b_i)}$ The input gate controls how much new information should be written into the cell state.

Candidate Cell State. $\boldsymbol{\tilde{c}_t = tanh(W_c\,[h_{t-1}, x_t] + b_c)}$. This step generates candidate values that may update the internal memory of the LSTM cell.

Cell State Update. $\boldsymbol{c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t}$ The cell state combines the retained information from the previous step with the new candidate values.

Output Gate $\boldsymbol{o_t = \sigma_o(W_o\,[h_{t-1}, x_t] + b_o)}$ The output gate determines which part of the cell state should be exposed to the next layer.

Hidden State $\boldsymbol{h_t = o_t \odot tanh(c_t)}$ The hidden state represents the output of the LSTM unit at time step $\boldsymbol{t}$.

In the proposed approach, the activation functions within the LSTM architecture are parameterised and interpreted as adaptive membership functions, allowing the network to perform fuzzy inference directly within its recurrent structure.

Computational Experiment

Description of the Computational Experiment

Data Collection The data used in the computational experiments were obtained from the Yahoo Finance platform using the yfinance Python library (Aroussi, 2025). For the analysis and forecasting tasks, historical quotations of BTC-USD (Bitcoin to US dollar) were used with three different temporal resolutions: 1 minute, 1 hour, and 1 day.

The experimental periods were defined as follows:

- 1-minute interval: the most recent week of available data;
- 1-hour interval: the previous 730 days;
- 1-day interval: the entire available historical record.

The collected data were preprocessed using normalisation followed by the proposed fuzzification procedure. After preprocessing, the dataset was divided chronologically into training (75 %) and testing (25%) subsets. This temporal split ensures realistic forecasting conditions and prevents data leakage between past and future observations. The original time series values ranged approximately from 20,000 USD to 120,000 USD, which should be taken into account when interpreting the forecasting performance metrics.

Evaluation Metrics. To evaluate forecasting performance, three commonly used regression metrics were computed for both the training and testing datasets after reversing the normalisation applied during preprocessing. The following metrics were used: RMSE (Root Mean

Squared Error), MAE (Mean Absolute Error), MAPE (Mean Absolute Percentage Error). All evaluation metrics were computed using the scikit-learn library after denormalising both predicted and observed values using the same scaler applied during the preprocessing stage. Lower values of these metrics indicate higher forecasting accuracy.

Experimental Setup The models were trained for 100 epochs with a batch size of 32. For financial time series forecasting, the mean squared error (MSE) was used as the loss function, while the Adam optimiser was employed for parameter optimisation. The hyperparameters of the models varied depending on the time resolution of the dataset. The corresponding parameter settings are presented in Table 2.

Table 2. Parameter settings for each model depending on the time tick.(Kumskov et al., 2025)

Tick	Units	Lookback
1m	16	30
1h	16	30
1d	16	1

LSTM The baseline LSTM model without fuzzification or parametric activation functions. Input dimension:$(lookback, 1)$. The architecture consists of: one $LSTM(units)$ layer, one $Dense(1)$ output layer.

Fuzzy Gauss An LSTM model with additional Gaussian fuzzification applied during data preprocessing. Local volatility (interpreted as the width of the Gaussian membership function) was calculated over the previous $window = 10$ observations. Input dimension:$(lookback, 2)$. The architecture consists of: one $LSTM(units)$ layer, two $Dense(1)$ layers.

PFS An LSTM model with fuzzification based on Probabilistic Fuzzy Sets (PFS).The number of intervals was fixed at $n = 14$ as suggested in the original method. Input dimension:$(lookback, n)$. The architecture consists of: one $LSTM(units)$ layer, one $Dense(n)$ layer.

Fuzzy Activation. An LSTM model with parametric activation functions. Three different configurations were considered:

1. Shared parametrization. All three sigmoid activation functions within the LSTM share the same parameters (+2 additional parameters).
2. Independent parametrization. Each of the three sigmoid activation functions has its own parameters (+6 additional parameters).
3. Full parametrization. All five activation functions in the LSTM are parameterised, with the tanh function replaced by a parametric sigmoid (+10 additional parameters).

Increasing the number of parameters leads to longer training times. Input dimension:$(lookback, 1)$. The architecture consists of: one $LSTM(units)$ layer, one $Dense(1)$ layer.

Fuzzy LSTM. The final proposed model combines fuzzification at the preprocessing stage with parametric activation functions inside the LSTM network. For the computational experiment, the configuration that demonstrated the best performance was selected: Fuzzy Gauss + Fuzzy Activation Variant 1 (i.e., Gaussian fuzzification combined with a single parametric sigmoid).

Software Implementation

All experiments were implemented in Python using the Google Colab environment. The following libraries were employed during the experiments: TensorFlow, NumPy, Pandas, Matplotlib, and Scikit-learn. The implementation of the proposed models, together with the scripts

used for the experiments, is publicly available at: github.com/MakhovaAnastasia/Paper_Fuzzy_LSTM

Results of the Computational Experiment

Minute Ticks For the minute-level time series, most of the proposed models demonstrated improved forecasting performance compared with the baseline LSTM model. In particular, the Fuzzy Gauss and Fuzzy LSTM architectures achieved the best results, with the Fuzzy LSTM model showing slightly higher overall accuracy. The forecasting performance improved by approximately 1.3 times compared with the standard LSTM model.

The PFS model demonstrated significantly worse performance. This behaviour can be explained by the large number of fuzzy variables generated at each time step, which increases model complexity and makes the model more sensitive to noise in the data. For this reason, the PFS model was excluded from further experiments with other time resolutions.

The results for the minute-level experiments are presented in Table 3.

Table 3. Comparison of forecasting results for different models on minute-level ticks. The best results are highlighted in bold.

Model	Training			Testing		
	RMSE ($)	MAE ($)	MAPE (%)	RMSE ($)	MAE ($)	MAPE (%)
LSTM	54,9733	37,3272	0,0318]	58,3047	34,8402	0,0283
Fuzzy Gauss	44,8551	29,6470	0,0253	**47,0182**	26,8458	0,0218
PFS	140,6855	73,6051	0,0626	337,3356	275,9606	0,2399
Fuzzy Activation 1	52,9521	35,8788	0,0306	57,5777	35,5182	0,0288
Fuzzy LSTM	**44,8499**	**29,6360**	**0,0253**	47,0379	**26,8441**	**0,0218**

Hourly Ticks For the hourly time series, all proposed models demonstrated better performance than the baseline LSTM model. Among them, the Fuzzy LSTM architecture achieved the best overall forecasting accuracy.The improvement in forecasting performance reached approximately 1.7 times compared with the standard LSTM model. The detailed results for hourly ticks are summarised in Table 4.

Table 4. Comparison of forecasting results for different models on hourly ticks. The best results are highlighted in bold.

Model	Training			Testing		
	RMSE ($)	MAE ($)	MAPE (%)	RMSE ($)	MAE ($)	MAPE (%)
LSTM	443,5242	314,5747	0,4826	569,2924	464,7323	0,4305
Fuzzy Gauss	**390,0027**	241,2795	**0,3570**	394,6866	266,7668	0,2518
Fuzzy Activation 1	410,3983	268,9249	0,4020	513,1758	400,4491	0,3708
Fuzzy LSTM	390,0251	**241,2554**	0,3571	**393,1039**	**264,9332**	**0,2502**

Daily Ticks. For the daily time series, the results showed a different behaviour. In this case, Gaussian fuzzification alone led to a decrease in forecasting accuracy. However, the use of parametric activation functions and the proposed Fuzzy LSTM model improved the forecasting performance. Overall, the proposed model increased forecasting accuracy by approximately 1.5 times compared with the baseline LSTM model. The detailed results are presented in Table 5.

Table 5. Comparison of forecasting results for different models on daily ticks. The best results are highlighted in bold.

Model	Training			Testing		
	RMSE ($)	MAE ($)	MAPE (%)	RMSE ($)	MAE ($)	MAPE (%)
LSTM	806,8518	424,393 1	14,9362	2564,027 8	1723,623 2	2,3658
Fuzzy Gauss	810,5163	448,118 0	21,7077	1665,308 4	1096,931 8	1,7346
Fuzzy Activation 1	836,4935	**393,587 1**	**3,3283**	3180,911 1	2204,956 9	2,9519
Fuzzy LSTM	**804,5797 6**	423,186 4	16,7181	**1660,937 6**	**1092,267 0**	**1,7307**

Training Time. Because the proposed models introduce additional parameters, the total training time increased compared with the baseline LSTM architecture. The corresponding training times for all models are presented in Table 6.

Table 6. Training time of the models for different time intervals.

Model	Number of additional parameters	Training time (sec)		
		1m	1h	1d
LSTM	0	91.14	300.63	40.58
Fuzzy Gauss	$1 \cdot lookback$	90.14	314.33	42.83
PFS	$(m-1) \cdot lookback$	222.60		
Fuzzy Activation 1	2	108.62	406.26	44.44
Fuzzy LSTM	$2 + 1 \cdot lookback$	111.65	393.45	46.51

Discussion and Experimental Conclusions

The experimental results demonstrate that the proposed fuzzy logic-based LSTM architecture improves forecasting performance across different temporal resolutions. Specifically, the forecasting accuracy increased by approximately 1.3 times for minute-level data, 1.7 times for hourly data, and 1.5 times for daily data compared with the baseline LSTM model. In addition, for daily observations the proposed approach reduced the MAPE value by a factor of 4.4, indicating a substantial improvement in relative forecasting accuracy

The difference in forecasting accuracy across time resolutions can be explained by the scale and complexity of the data. At hourly and daily intervals, many external factors influencing future price movements are not directly captured by the input data. As a result, the model has access to less detailed temporal information, which leads to lower predictive accuracy. Consequently, forecasts based on minute-level data are generally more accurate than hourly forecasts, while hourly forecasts outperform daily predictions.

The training dynamics of the models were also analysed. In most experiments, the loss function quickly reached an asymptotic level after approximately 10–20 training epochs. Furthermore, the loss curves for the training and testing datasets exhibited similar behaviour, indicating stable convergence of the models and the absence of significant overfitting.

Conclusion

In this work, we developed a neural network architecture with memory enhanced by fuzzy logic for financial time series forecasting. Introducing fuzziness both at the data preprocessing

stage and within the neural network significantly improved forecasting accuracy compared with the baseline LSTM model: by approximately 1.3 times for minute-level data, 1.7 times for hourly data, and 1.5 times for daily data. The proposed approach integrates fuzzy logic directly into the learning process of the model and improves the interpretability of the network's decision-making mechanism.

The obtained results demonstrate the potential of combining fuzzy logic and deep learning techniques for modelling complex financial time series. Several directions for future research appear promising. In particular, further work may include:

- exploring alternative parametric activation functions, including parameterised versions of the tanh function;
- applying linguistic variables for the classification of market states and trend dynamics;
- incorporating reinforcement learning methods to design adaptive forecasting strategies and portfolio management approaches based on predicted values;
- extending the evaluation of the proposed model to a wider range of financial instruments and market conditions.

Another promising direction for future research is the decomposition of financial time series into low-frequency and high-frequency components. The low-frequency component typically represents the underlying market trend, while the high-frequency component corresponds to short-term fluctuations around this trend. In such a framework, fuzzification can be applied to the trend component using several shifted fuzzy sets (for example, left-shifted, centred, and right-shifted membership functions). This representation allows the model to capture deviations of the observed signal from the underlying trend. The high-frequency component, which oscillates around the trend, can therefore be interpreted and modelled through these fuzzy representations, enabling the model to detect short-term fluctuations and noise more effectively.

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PARTICLE PLACEMENT IN AN ATOM BASED ON THE FERMI-DIRAC AND BOSE-EINSTEIN DISTRIBUTION ACCORDING TO THE VALUE OF THE SPIN QUANTUM NUMBER

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Abstract. *The article discusses the significance of the arrangement of atoms and molecules in a substance that forms stable systems, such as an atom and a molecule. It examines the patterns of combining elementary particles, such as electrons and nuclei, which are present in nature, to form atoms, as well as their distribution within an atom. The article provides information about the differences in elementary particles, which have been verified by scientists, based on their spin values, and how they follow different distributions based on their spin values, as well as their arrangement within an atom based on the Pauli principle. The Fermi-Dirac and Bose-Einstein distributions are the fundamental concepts of atomic and molecular physics and provide a complete answer to the question of whether the system and the physical properties of a molecule or an atom depend on the arrangement of the elementary particles that make up the system.*

Keywords: *elementary particles, distribution law, Fermi-Dirac distribution, Bose-Einstein distribution, spin, Pauli principle, fermion, boson.*

Introduction

In nature, atoms and molecules occur both as individual systems and, through mutual combination, form higher-level systems—substances. As we know, substances occur in nature in four aggregate states. So what exactly distinguishes these states from one another? Even substances with identical composition are not uncommon in nature when they differ in their physical properties and characteristics. Therefore, the main reason for the variation in the properties of matter must be some factor other than its structural composition. In classical physics, the molecules and atoms in matter are regarded as stable systems composed of associations of elementary particles. However, after 1900, as knowledge of quantum physics took shape, it became clear that the small systems forming the basis of matter actually obey the laws of quantum physics. For example, based on Niels Bohr's postulates on atomic structure, it was proven that the atomic system is a complex quantum system. The nucleus and electron within the system are themselves quantum systems, and there are specific laws governing their behavior as a whole. These laws, following the discovery of electron and nuclear spin, established the conditions for the stability of the atomic system.

We classify the numerous elementary particles found in nature according to their charge, rest mass, lifetime, and spin quantum number. Essentially, elementary particles are divided into those with integer spin quantum numbers and those with half-integer spin quantum numbers. We group particles with an integer spin quantum number as bosons and those with a half-integer spin quantum number as fermions. Fermions include quarks (adron, baryon, nucleon, atom, molecule) and lepton particles, while bosons include photon, gluon, and graviton particles.

Atoms and molecules that participate in the formation of matter are composed precisely of these elementary particles. Therefore, once the existence of the electron within the atom was proven, all atoms in nature were considered to have been formed as a result of electron-nucleus interactions, these atoms should differ from one another in the number of electrons and in the arrangement of electrons in their orbitals and in their energy states, and an answer to this question was not found quickly. In 1922, according to the atomic model proposed by Niels Bohr, electrons confined to a single orbit occupy stable “closed shells” corresponding to the numbers 2, 8, 18, … . Pauli attempted to explain these empirically determined numbers. In a 1924 scientific paper published by Stoner, it was suggested that the numbers proposed by Bohr could be the value of the principal quantum number; Pauli, on the basis of this scientific idea, attempted to explain these empirically determined numbers.

Analysis of relevant literature (Literature review).

Macroscopic systems consist of a very large number of molecules and atoms. The molecules in these systems are arranged according to certain laws. The motion of molecules and atoms can be explained by the laws of classical or quantum mechanics. For example, L. D. Landau and E. M. Lifshitz. In the book “Course of Theoretical Physics, Vol. 5: Statistical Physics, Part 1” [1], it is stated that “According to statistical laws, because bodies consist of a large number of particles, their motion cannot be fully explained by the laws of classical mechanics.” The distribution laws for particles differ, and depending on which wave function is used to describe their motion—namely whether they have symmetric or antisymmetric wave functions—their spin value is distinguished as integer or half-integer. If the particle spin has half-integer quantum numbers, then the Pauli principle applies, and there can be no more than one particle in each quantum state; the distribution is described by the Fermi–Dirac distribution. Conversely, if the particle spin has integer quantum numbers, it is described by a symmetric wave function, and any number of particles can occupy each quantum state. This particle distribution is called the Bose–Einstein distribution. According to the Bose–Einstein distribution, the number of particles in gases is calculated using the formula $N = \frac{gVm^3}{2^{1/2}} \frac{16\pi}{h^3} \int_0^\infty \frac{\sqrt{\varepsilon} d\varepsilon}{e^{(\varepsilon-\mu)/T} \pm 1}$. The author suggested that particles distribute differently in solids or gases depending on the value of their spin quantum number, and that in statistical analysis the appropriate distribution for a given particle should be determined precisely by that quantum number value.

When we analyze A.I. Morozov's “Electronic Fermi Liquid in Metals, 2016” [2], the author examines the filling of electronic states at absolute zero temperature, Since fermions obey the Pauli principle, in the given case, according to the complete set of quantum numbers, there should not be more than one electron. As we know, at absolute zero temperature the system is in its lowest energy state; we fill the states in order of electron energy, which increases monotonically. All quantum states have wave vectors in the state, The electrons' Fermi wave vector corresponds to the Fermi momentum. The threshold energy between $|k| \le k_F$ occupied and unoccupied states is called the $k_F = (3\pi^2 n_e)^{1/3} \approx 10^{10} m^{-1}$

Fermi energy - $E_F = \frac{h^2 k_F^2}{8\pi^2 m} = \frac{p_F^2}{2m}$. Accordingly, from the equality, the electron's Fermi momentum is $p_F = \frac{h}{2\pi} k_F = 10^{-24} kg \cdot m/s$.

Research Methodology

To ensure our students fully grasp the topic, we must first explain the structural composition of complex systems like molecules and atoms, as well as quantum states, quantum numbers, and the Pauli principle, and then explain the laws of distribution. In molecular physics, the Maxwell distribution of molecular velocities and the Boltzmann distribution of pressures are studied. If a student has mastered these topics well, they will know that elementary particles, such as electrons in the atoms that make up molecules, can change their speed during their motion. That is, based on which energy level the electron occupies in the atomic system, its momentum and velocity can be calculated.

Initially, to explain the topic, we will use the comparative method to study the general and specific parameters of the Bose-Einstein, Fermi-Dirac, and Boltzmann distributions.

Boltzmann distribution	**Fermi-Dirac distribution**	**Bose-Einstein distribution**
$< n >= \frac{1}{\exp(\frac{\varepsilon - \mu}{k_B T})}$	$< n >= \frac{1}{\exp(\frac{\varepsilon - \mu}{k_B T}) - 1}$	$< n >= \frac{1}{\exp(\frac{\varepsilon - \mu}{k_B T}) + 1}$
The particles are the same	The particles are the same	The particles are the same
$Z = (Z_1)^N / N!$ $n << 1$	The spin quantum number is an integer: (0,1,2,...)	The spin quantum number is a half-integer: (1/2, 3/2, 5/2...)
Spin is irrelevant	Bozons	Fermions
Particles are localized (not represented by a ψ function)	The ψ function representing the state of the particles is completely symmetric.	The ψ function representing the state of the particles is fully antisymmetric.
Gas molecules at the lowest density	Photons, atoms, ^4He	Electron, proton, neutron
The number of particles in the microenvironment is unlimited.	The number of particles in the microenvironment is unlimited.	In a single quantum state, there cannot be more than one particle with the same quantum numbers.

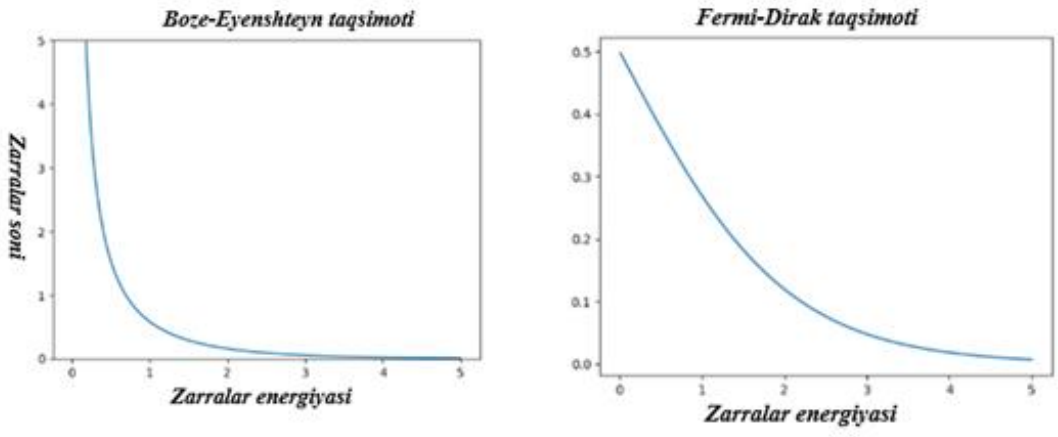


Figure 1. Graph of the Bose-Einstein and Fermi-Dirac distributions for the same parameter.

Based on the distribution of particles by velocity and pressure, we determine that, according to their quantum number values, they obey Fermi–Dirac and Bose–Einstein distributions. Since the elementary particles in the atomic system—electrons, protons, and neutrons—are fermions, they obey the Fermi-Dirac distribution. Looking at the Fermi-Dirac distribution graph, no sharp spikes are observed in the graph of the number of particles versus particle energy, in accordance with the Pauli principle. The curve changes gradually as the temperature decreases. Also, if we compare it with the Bose-Einstein distribution graph for bosons, such as the photon, we see that the photon's energy can be zero, which is evident in the graph. For fermions, however, the energy cannot be zero. Bose-Einstein statistics describe how bosons are more likely to be found in the lowest energy state.

In quantum mechanics, unlike classical mechanics, a particle moving in a specific quantum state undergoes finite motion. Each quantum state has multiple energy levels distinguished by the spin quantum number. In finite motion, each energy level takes on discrete values. The electron gas obeys the Fermi–Dirac distribution; according to the Pauli principle, free electrons interact with each other, and this interaction is not forceful but quantum in nature. That is, a free electron is not absolutely free. The Fermi-Dirac distribution of electrons in the electron gas is:

$$f(E,T)=\left\{1+\exp\frac{E-E_p}{kT}\right\}^{-1}$$

E_p - The value of the Fermi-Dirac function is always equal to ½. This function determines the maximum number of electrons with energy E that can exist in a single quantum state. The Bose–Einstein distribution applies to an ideal gas of free bosons. The bosons do not interact with external fields or with each other. The particle's state, in terms of its momentum and spin projection, takes only two values according to the $g=2s+1$ Landé factor. The number of states p and $p+dp$ in the range of momentum values and is calculated using the $dN_p=\frac{gV4\pi}{h^3}p^2dp$ formula .

Analysis and results

An atom is a stable system, and its constituent particles are the electron and the proton, Since the neutron is a fermion, knowing the distribution of electrons across an atom's energy levels is extremely important, because atomic systems—by virtue of having the same electrons arranged in different energy states in varying numbers and energy levels—produce different atoms. Therefore, students are observed to master the Fermi-Dirac distribution well based on their strong understanding of the unique and common properties of boson and fermion particles. The Fermi-Dirac distribution, in turn, provides the basis for accurately calculating the energy levels of electrons, protons, and neutrons in an atom. In Dirac's formula for calculating the energy of the relativistic electron, the sum of the electron's momentum and its intrinsic magnetic moment is included in the total momentum. This quantity, in turn, differs for each of the electron's energy levels. In the Fermi-Dirac distribution, the level energy of electrons depends on the magnitude of the Fermi wave vector. The value of the Fermi wave vector, in turn, is determined by the energy level of the orbit in which the electron is moving.

Students understand that the main difference between the Fermi–Dirac distribution and the Bose–Einstein distribution is that the former is valid only for fermions—which, by Pauli's principle, can occupy atomic energy levels with a half-integer spin quantum number—and that

they can move within those levels. As a result, when filling atoms with electrons according to the Mendeleev system of chemical elements, they place exactly one electron in each state with exactly the same set of quantum numbers, based on the values of the spin quantum number's projections onto the spatial axes. As a result of understanding how electrons are arranged in an atom, they come to understand why the first period elements are filled with hydrogen and helium.

In molecular physics, the Maxwell, Bose-Einstein, and Fermi-Dirac distributions study the arrangement of molecules within materials. Considering that the atoms from which molecules are composed also obey these same laws, The Fermi-Dirac distribution is considered the primary distribution explaining the arrangement of electrons in an atom. This is because electrons in atoms simultaneously undergo very complex motions. As a result, atoms with the exact same number of electrons are observed to have two different energies at the same time. The primary reason for this is the change in the value of the resulting spin due to the orientation of the electrons. For example, the helium atom, which has only two electrons, when transitioning to excited levels, can exist in two orthogonal spin states: the parahelium state with spin zero and the orthhelium state with spin one. According to the Dirac equation, the total energy yields two different values. As a result, in the multiplet state, fine structure singlet and triplet splittings occur.

Conclusion/Recommendations

In conclusion, it can be said that electrons in atoms are arranged according to a specific pattern. We studied how the spin—the intrinsic moment that arises from electrons' rotation around their own axis in addition to their orbital motion around the nucleus—causes their orientation to change in energy levels. Since the spin magnetic quantum number can only take on two values, electrons in a single energy level can only have two orientations. As a result, students can write the electron formula and configuration of an element's atom by filling its energy levels with electrons in antiparallel arrangement. For this, they must have a good grasp of the differences between the distributions and their importance in distinguishing particle locations.

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STUDY OF THE PHYSICOCHEMICAL PROPERTIES OF WORN AUTOMOBILE TIRES FOR USE AS MODIFIED BITUMEN COMPONENTS

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Abstract. *This study presents a comprehensive physicochemical investigation of carbon-containing material obtained from thermo-oxidative pyrolysis of worn automobile tires at an industrial unit with a capacity of one ton per day. Thermal degradation behavior was analyzed using a Labsys Evo (Setaram) derivatograph, revealing a two-stage decomposition process occurring within 50–500 °C and 500–800 °C. The total mass loss reached 48.8% at 900 °C, indicating substantial conversion of the organic rubber matrix and formation of a stable carbonaceous residue. Morphological analysis performed using a scanning electron microscope (EVO MA 10) under vacuum conditions demonstrated a heterogeneous, porous structure with dispersed metallic inclusions. Energy-dispersive X-ray spectroscopy (EDS) confirmed that the material predominantly consists of amorphous carbon (approximately 72–73 wt.%) along with oxygen, zinc, iron, and minor mineral components originating from tire additives. Particle size reduction improved bulk density and surface activity, while magnetic separation effectively removed metallic impurities. The obtained carbon-containing material can be recommended as a functional filler for polymer-modified bitumens used in road construction, contributing to enhanced mechanical performance, improved thermal stability, and sustainable recycling of waste tires.*

Keywords: *Thermo-oxidative pyrolysis; waste tire recycling; carbon-containing material; thermogravimetric analysis (TGA); SEM–EDS analysis; particle size distribution; polymer-modified bitumen; asphalt pavements; sustainable road materials; carbon black filler.*

Introduction

The rapid growth of automobile transport has led to a continuous increase in the accumulation of worn automobile tires, creating serious environmental and technological challenges worldwide. Waste tires are characterized by high durability, chemical resistance, and slow natural degradation, which makes conventional disposal methods environmentally unsafe and economically inefficient [1,2]. Among various recycling technologies, pyrolysis has emerged as one of the most promising approaches due to its ability to convert waste rubber into valuable products, including pyrolysis oil, gas fractions, and carbon-containing solid residue [3–5]. Thermal degradation of tire rubber is a complex multistage process involving devulcanization, polymer chain scission, and carbonization of organic components.

Thermogravimetric studies have demonstrated that rubber materials typically undergo two or three main degradation stages depending on heating conditions and atmosphere [6–8]. The first stage is associated with the decomposition of natural and synthetic rubber components, while the second stage corresponds to further carbonization and decomposition of carbonaceous structures [7,9]. Quantitative thermal analysis provides essential data for optimizing pyrolysis parameters and predicting product yields [6]. The solid carbonaceous residue obtained after pyrolysis consists mainly of amorphous carbon, residual inorganic fillers, and metallic inclusions originating from tire reinforcement elements [10-12]. Its structure and surface morphology strongly influence potential application fields.

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) are widely applied to characterize the microstructure and elemental composition of pyrolysis-derived carbon materials [13-15]. Previous studies have reported that carbon content in tire pyrolysis char may exceed 70 wt.%, with zinc oxide, silica, and iron compounds as the main inorganic components [10,16]. Due to its high carbon content and developed porous structure, pyrolysis-derived carbon material has attracted attention as a reinforcing filler in polymer systems [17–19]. Carbon black is traditionally used in polyethylene, polypropylene, polyvinyl chloride, and elastomeric materials to enhance mechanical strength, thermal stability, and resistance to photo-oxidative aging [20-22]. The possibility of replacing commercial carbon black with pyrolytic carbon offers significant economic and environmental advantages [16].

In recent years, growing interest has also been directed toward the application of recycled rubber products and carbonaceous materials in road construction. Polymer-modified bitumens (PMB) are widely used to improve rutting resistance, fatigue life, and low-temperature performance of asphalt pavements [24,25]. Incorporation of crumb rubber and carbon-based fillers into bitumen has demonstrated improvements in elasticity, thermal stability, and aging resistance [24]. However, detailed studies of pyrolysis-derived carbon materials as fillers for modified bitumens remain limited. Therefore, comprehensive investigation of the thermal behavior, morphology, elemental composition, and physicochemical characteristics of pyrolysis-derived carbon-containing material is necessary to justify its application in polymer-modified bitumens for road construction.

The present study aims to evaluate these properties and determine the feasibility of utilizing this secondary carbon product as a functional filler in modified bituminous systems. Recent studies have demonstrated the effectiveness of incorporating secondary industrial by-products into polymer–bitumen compositions to enhance thermal stability, frost resistance, and mechanical performance. Yoqubov et al. (2023) developed a polymer–bitumen insulating composition based on petroleum bitumen and secondary products of the chemical industry, including pyrolysis resin, carbon-containing materials derived from worn-out tires, and crushed tire powder. Their investigation showed that crumb rubber undergoes swelling and partial devulcanization at 180 °C within 6–8 hours, forming an active structural network within the bituminous matrix. The addition of gas pyrolysis resin (3–5 wt%) significantly increased the softening temperature of the composition by up to 120 °C, improving thermal stability.

Furthermore, carbon-containing material obtained via tire pyrolysis was shown to enhance adhesion strength and heat resistance due to its high amorphous carbon content (approximately 88%) and active surface structure confirmed by IR and X-ray diffraction analyses. The incorporation of secondary alkanolamines as vulcanization accelerators (5 wt%) contributed to improved structural formation and resistance to extreme climatic conditions [26]. These findings

confirm that the integration of recycled industrial materials not only improves the physicochemical and mechanical characteristics of polymer–bitumen systems but also increases sustainability and resource efficiency, which is particularly important for regions with sharply continental climates.

Materials and Methods. Thermal analysis of worn automobile tires was carried out using a modern derivatographic technique, which enables the simultaneous determination of mass variation (TG), mass loss rate (DTG), and thermal effects (DSC) over a broad temperature range. The experiments were performed on a Labsys Evo (Setaram) thermal analyzer. The resulting derivatogram is presented in Figure 1. The morphology and elemental composition of the carbon-containing material obtained after thermo-oxidative pyrolysis were investigated using a scanning electron microscope (SEM) of the EVO MA 10 brand under vacuum conditions. Elemental analysis was performed using an integrated energy-dispersive X-ray spectroscopy (EDS) detector.

Results and Discussion. The thermogravimetric (TG) curve (Figure 1) demonstrates a two-step degradation mechanism, characterized by two distinct sigmoidal regions corresponding to successive stages of thermal decomposition. The first degradation stage occurs within the temperature range of 50–500 °C, while the second stage is observed between 500 and 800 °C. In the first temperature interval (50–500 °C), the sample exhibits a mass loss of 17.9 mg, corresponding to 40.6% of the initial mass. This stage is associated with intensive thermal decomposition of the rubber matrix, during which the maximum degradation rate reaches 2.508 mg/min.

The rapid mass reduction in this region is attributed to polymer chain scission, release of volatile components, and partial devulcanization processes. The second degradation stage, occurring between 500 and 800 °C, proceeds at a comparatively lower rate of 1.837 mg/min. In this temperature range, the overall mass loss increases from 40.6% to 46.6%. This stage is primarily related to further carbonization of the residual organic structure and gradual breakdown of carbonaceous components. At 900 °C, the total mass loss reaches 48.8%, while the remaining solid residue corresponds mainly to metallic cord reinforcements and inorganic fillers originally present in the tire structure. The obtained results confirm the multistage thermal degradation behavior of worn rubber materials and provide quantitative parameters necessary for optimizing pyrolysis and recycling processes.

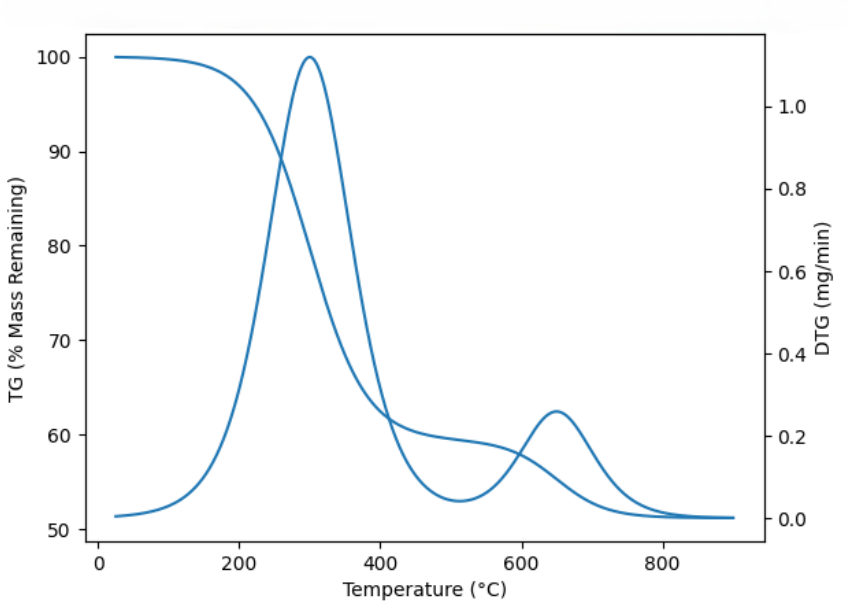


Figure 1. Derivatogram of Worn Automobile Tires (Labsys Evo Setaram)

At the Central Mining Department of the Navoi Mining and Metallurgical Combine, a pyrolysis unit with a capacity of one ton per day is currently in operation. Therefore, in order to identify and expand the potential application areas of the carbon-containing material obtained, a detailed study of its physicochemical characteristics is required. During the thermo-oxidative pyrolysis process, a carbon-containing material is formed. It is a relatively brittle, lump-like substance of black color with a grayish tint and an unpleasant odor (Fig. 2a). In some fragments, metallic inclusions are observed (Fig. 2b).

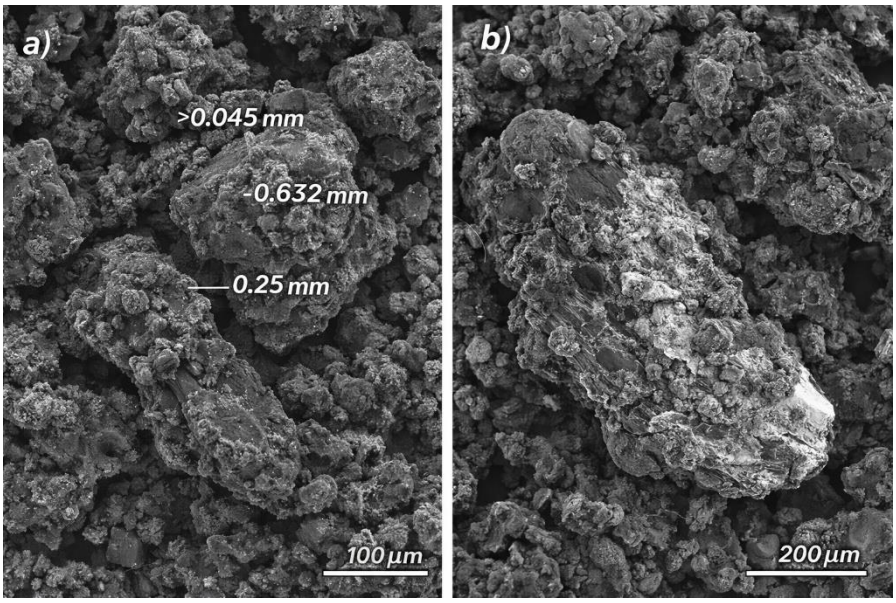


Figure 2. Microscopic general view of the carbon-containing material after pyrolysis.

Prior to use, the technical carbon was ground using a laboratory jaw crusher (model BB 600). Analysis of the results (Fig. 2) shows that the particles of the carbon-containing material vary in size. Among the particles, those larger than 0.045 mm and smaller than 0.25 mm (0.045 < d < 0.25 mm), with an average size of approximately 0.062 mm, account for 62.0% of the total particle content. Particles in the size range from 0.062 mm to 0.5 mm (approximately 0.25 mm fraction) represent 23.0 wt%. Additionally, particles with a size of 0.5 mm constitute about 10.0 wt%. The use of carbon-containing material containing finely dispersed metallic inclusions as a filler in rubber products negatively affects the quality of rubber goods. To remove these metallic inclusions, magnetic separation is applied.

After grinding, the carbon-containing material becomes a dispersed powder of dark black color. The ground carbon-containing material can be recommended as a filler for polymers and polymer-based materials. Carbon black is mainly used as a structural filler for polyethylene, polypropylene, polyvinyl chloride, and other polyolefins. The incorporation of carbon black enhances the durability of polymer materials and improves their resistance to photo-oxidative aging. The physicochemical characteristics of the carbon-containing material before grinding (CM-1) and after grinding (CM-2) are presented in Table 1.

Table 1. Physicochemical characteristics of the carbon-containing material before grinding (CM-1) and after grinding (CM-2).

Properties	**Rn, g/sm^3**	**pH**	**A^d, %**	**W^a, %**
CM-1	0,324 ± 0,02	6,4	21,66 ± 0,44	0,23 ± 0,05
CM-2	0,407 ± 0,02	6,4-5,5	23,71 ± 0,44	0,40 ± 0,05

The analysis of the results indicates that reducing the particle size of the carbon-containing material leads to an increase in bulk density, acidity, and moisture content, while having practically no effect on ash content. SEM micrographs (Fig. 2a, b) reveal that the carbon-containing material has a heterogeneous structure characterized by irregularly shaped particles with a rough and porous surface morphology. The particles exhibit varying sizes, confirming the polydispersity of the material after grinding. In several regions, bright contrast areas are observed, corresponding to metallic inclusions embedded within the carbon matrix. These inclusions are attributed to residual metallic cord components originating from worn automobile tires.

The EDS spectrum confirms that carbon is the dominant element in the material, accounting for approximately 72–73 wt.%, which is consistent with the formation of a carbon-rich pyrolysis product. Oxygen is present at about 14 wt.%, indicating partial surface oxidation during thermo-oxidative processing. Zinc (approximately 9 wt.%) is detected as one of the major inorganic components, which is typically associated with zinc oxide used in tire formulations as a vulcanization activator (Figure 3).

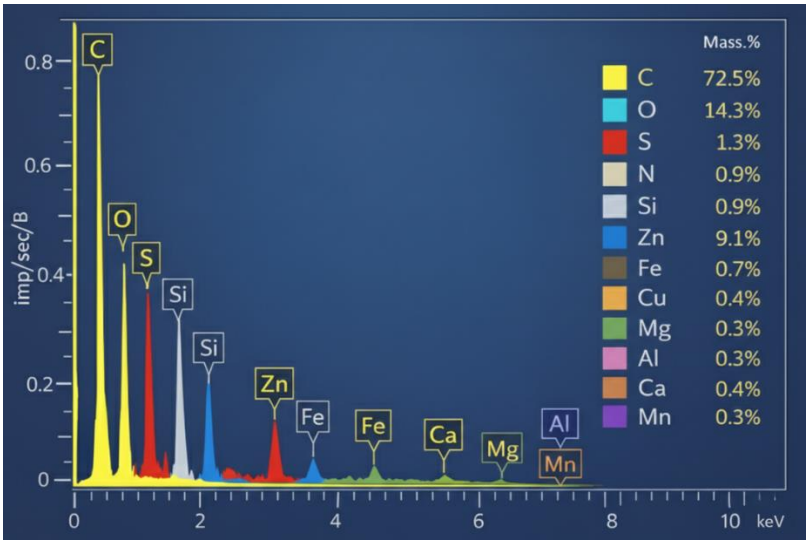


Figure 3. EDS spectrum of the carbon-containing material after pyrolysis.

Minor amounts of sulfur (1–2 wt.%) confirm the presence of vulcanization residues. Silicon, calcium, magnesium, and aluminum are detected in small concentrations, indicating the presence of mineral fillers such as silica and other inorganic additives used in tire manufacturing. Iron and copper peaks correspond to metallic cord residues and reinforcing wire fragments. Trace amounts of manganese are also detected (Table 2). The results demonstrate that the pyrolysis-derived carbon-containing material consists predominantly of amorphous carbon with dispersed inorganic and metallic phases. The presence of residual metallic inclusions justifies the application of magnetic separation prior to its use as a filler material.

Overall, the combined SEM and EDS analysis confirms that the obtained product possesses structural and compositional characteristics suitable for use as a reinforcing filler in polymeric and composite materials, provided that metallic impurities are effectively removed.

Table 2. Elemental composition of automobile tire sample determined by EDS analysis:

Element	**C**	**O**	**S**	**N**	**Si**	**Zn**	**Fe**	**Cu**	**Mg**	**Al**	**Ca**	**Mn**
Mass, %	72.5	14.3	1.3	1.9	0.9	9.1	6.1	0.7	0.4	0.3	0.3	0.3
σ	1.0	0.7	0.1	0.2	0.2	0.6	0.6	0.1	0.1	0.1	0.1	0.1

Conclusions

A comprehensive thermal, morphological, and elemental analysis confirmed that worn tires undergo a two-stage degradation process through thermal-oxidative pyrolysis, resulting in the formation of a carbon-rich solid residue. Thermogravimetric data indicate a 48.8% mass retention at 900°C, indicating the development of organic rubber matrices and the formation of thermally stable carbon structures. Scanning electron microscopy (SEM) analysis revealed a heterogeneous porous morphology with dispersed metallic inclusions, while material dispersive analysis (EDS) results established that the primary composition is amorphous (72–73 wt%), including minor amounts of inorganic components such as Zn, Fe, Si, and Ca, derived from tire components and reinforcing elements. Reducing particle size increases bulk irradiance and surface activity without compromising the environmental impact of ash content, thereby maximizing the material's dispersibility and interaction potential. After magnetic separation to remove residual metals and inclusions, the resulting carbon-containing material can be effectively used as a functional filler for polymer-modified bitumen for road construction applications. Its rich carbon composition, developed surface structure, and adhesion to hydrocarbon chains provide mechanical strength, resistance to rutting and thermal cracking, and increased stability of asphalt concrete pavements. Thus, a method is proposed for using supports to improve the performance of modified bitumen and for sustainable recycling of waste tires for zero-waste technologies.

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DEVELOPMENT OF A MATHEMATICAL MODEL OF THE MECHANISM OF WATER ACCUMULATION, MOISTURE RETENTION AND WATER RELEASE BY BENTONITE CLAY

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Abstract. *One of the most important properties of bentonite clays is their high water retention capacity. Montmorillonite is the main rock-forming aluminosilicate mineral of bentonite clays, with an average content typically ranging from 60 to 70%. Due to its unique layered structure, montmorillonite can swell up to 14–16 times its original volume, while the "swelling–drying" cycle can occur repeatedly without limitation. This property can be utilized for the application of bentonite clays to enhance soil water retention capacity. In this study, a mathematical model describing the mechanism of moisture (water) accumulation by bentonite clay has been developed. The proposed model enables the development of technologies for the preparation and application of bentonite clay into soil, taking into account the properties and structure of bentonite and soil, as well as climatic and weather conditions.*

Keywords: *bentonite clay, mineral, montmorillonite, structure, water, soil, accumulation, mechanism, moisture, water retention, time, water retention model, absorption coefficient.*

Introduction

This paper presents the obtained data on the development of a mathematical model at the field level for water accumulation and release by bentonite in soil, taking into account the chemical–mineralogical composition, structure, and physicotechnical properties of major bentonite clay deposits, as well as the rainfed (non-irrigated) conditions of Uzbekistan. In constructing this mathematical model of water accumulation and release by bentonite in soil, methods for developing standard soil water retention curves of the van Genuchten type, standard models of bentonite water retention, and field data on bentonite application were used.

The scientific literature contains a number of studies aimed at investigating the use of bentonite clays for water accumulation and soil improvement in arid regions. For example, J. Mi and other researchers studied the effectiveness of applying bentonite clays at rates of 0–30 t/ha under field conditions over a period of five years. It was found that the optimal application rate was 24 t/ha, at which increases in soil moisture capacity, available water content, crop yield, plant photosynthesis, and water-use efficiency were observed, as well as a significant improvement in soil water retention capacity in semi-arid regions [1].

Long-term field experiments by J. Mi and other researchers demonstrated an increase in millet germination rate, accumulation of dry aboveground biomass, photosynthetic parameters, chlorophyll content, and water-use efficiency, as well as improvements in grain quality indicators (protein, fat, and fiber content). The application of 24 t/ha of bentonite had the greatest effect on plant productivity indicators averaged over five years, as well as on photosynthetic parameters averaged over three years (2013–2015), during which they were measured. An application rate of 18 t/ha had the greatest effect on grain quality. Bentonite, widely distributed in China, is a stable

mineral that requires only a single application and therefore has a clear advantage over synthetic water-absorbing polymers, which degrade within a few years and must be periodically reapplied to maintain their effect [2–5].

Hypothesis and initial data for constructing the mathematical model. It is assumed that, after being applied to the 7–10 cm layer, bentonite functions as an additional internal water reservoir. The total water storage in the root zone of the soil consists of water retained by the soil itself, water accumulated by bentonite, and losses due to evaporation, transpiration, runoff, and deep percolation. As a result of the conducted field studies, it was established that bentonite increases the water-holding capacity and the amount of available water in the 0–40 cm soil layer [10, 11]. In this case, the main initial variables and criteria for the calculation are as follows (table):

Table

Main initial variables and criteria for calculations in developing a field-level mathematical model of water accumulation and release by bentonite in soil

No.	Name of criterion	Criterion symbol	Unit of measurement
1	Time	t	day
2	Depth of the root zone	z_r	m
3	Depth of the bentonite application layer	z_b	m
4	Volumetric soil moisture	$\theta(t)$	m^3/m^3
5	Water storage retained by bentonite	$S_b(t)$	mm
6	Atmospheric precipitation	$P(t)$	mm/day
7	Infiltration into the layer	$I(t)$	mm/day
8	Total evaporation + transpiration	$ET(t)$	mm/day
9	Deep percolation below the roots	$D(t)$	mm/day
10	Surface runoff	$R(t)$	mm/day

Taking into account the initial calculation criteria adopted above, the basic water balance equation for the root zone has the following form:

$$W(t) = 1000\, z_r\, \theta(t) \tag{1}$$

where $W(t)$ is the soil water storage, in mm.

In this case:

$$\frac{dW}{dt} = I(t) - ET(t) - D(t) - R(t) + Q_b(t) \tag{2}$$

where $Q_b(t)$ is the water flux from bentonite into the soil. It should be noted that when $Q_b>0$, the bentonite releases water, and when $Q_b<0$, it absorbs water.

This mathematical expression reflects the essence of the cyclic, bidirectional reversible process of “water swelling – dehydration (water release)” in bentonite. In practice, according to this formula, bentonite is recharged (absorbs water) during winter and spring, and partially discharged (releases water) in summer [12–15]. The water storage within the bentonite structure, acting as a reservoir, depends on its capacity volume. The capacity of the bentonite reservoir is expressed by the following formula:

$$0 \le S_b(t) \le S_{b,\max} \tag{3}$$

In this case, the ratio of the change in water volume:

$$\frac{dS_b}{dt} = A(t) - L(t) \quad (4)$$

Where (t) is the water absorption by bentonite, and $L(t)$ is the release of water from bentonite to the soil and plants. In this case, water absorption is expressed by the following formula:

$$A(t) = k_a\, I_b(t) \left(1 - \frac{S_b}{S_{b,\max}}\right) \quad (5)$$

Where k_a is the absorption coefficient (0–1), and $I(t)$ is the portion of infiltration that actually reaches the layer with granules. According to research findings, the greater the available free capacity in the structure of a bentonite particle, the faster it accumulates (absorbs) water. The water release rate of bentonite is expressed by the following formula:

$$L(t) = k_r\, f_d(\theta)\, S_b \quad (6)$$

Where (k_r) is the release coefficient, day^{-1}, and $f_d(\theta)$ is determined by the following formula:

$$f_d(\theta) = \max\left(0, \frac{\theta_c - \theta}{\theta_c - \theta_{wp}}\right) \quad (7)$$

Where θ_c is the threshold below which the process of active water release begins, and θ_{wp} is the soil moisture. The rate of water release from bentonite depends on soil moisture; that is, when the soil is moist, bentonite releases almost no water. As the soil dries, the release increases. In this case, the mathematical form of this process takes the following expression:

$$Q_b(t) = L(t) - A(t) \quad (8)$$

The maximum water storage in bentonite, calculated per 1 hectare of land, can be defined in terms of the application rate:

$$S_{b,\max} = D_b \cdot w_{\max} \quad (9)$$

Where D_b is the bentonite application rate, kg/m^2, and $w_{\max}$ is the maximum water absorption, kg of water per kg of dry bentonite. To convert from t/ha, the following formula can be used:

$$D_b = \frac{\text{doze},\ t/ha \times 1000}{10000} \quad (10)$$

For example, when applying bentonite to the soil at a rate of 24 t/ha, the bentonite consumption per 1 m² is 2.4 kg/m²:

$$D_b = \frac{24 \cdot 1000}{10000} = 2.4\ \text{kg/m}^2 \quad (11)$$

Research results showed that applying bentonite to the soil at a rate of 24 t/ha is the optimal value determined through field trials conducted under semi-arid conditions. It was also established that the granules retain 0.8 kg of water per 1 kg of dry material. Therefore:

$S_{b,max}$=2,4·0,8=1,92 kg/m^2≈1,92 mm

If bentonite's water retention is 2–3 kg/kg, its capacity increases to 4.8–7.2 mm. This is not a fixed reference value for every specific bentonite but a calculated figure determined experimentally, depending on the chemical-mineralogical composition and structure, individually

for bentonite from each deposit [16–17]. As is well known, the main fertile soil layer in arid lands is located at the very top. For a layer with thickness (z_b), the mass fraction of bentonite application is given by:

$$\beta = \frac{M_b}{M_s} \quad (12)$$

Where (M_b) is the bentonite dose, kg/ha.

$M_s=10^4 \cdot z_b \cdot \rho_b$

Here, ρ_b is the bulk density of the soil, kg/m³.

Example: For z_b=0,10 m and ρ_b=1300 kg/m³, $M_s=10^4 \cdot 0{,}10 \cdot 1300=1{,}3\times10^6$ kg/ha

When applying bentonite to the soil at a rate of 24 t/ha:

$$\beta = \frac{24000}{1.3 \times 10^6} \approx 0.0185 \quad (13)$$

That is, bentonite will constitute about 1.5% by mass of the soil in the 0–10 cm layer. Where, AW — available water, mm;

θ_{FC} — moisture at field capacity;

θ_{WP} — soil moisture;

η — fraction of bentonite water actually available to plants.

In this case, the parameter η is needed because not all water retained by bentonite will necessarily be available to roots, which must be determined through experimental field trials [16–18]. In Central Asia, particularly in Uzbekistan, where a sharply continental climate prevails—a type of temperate climate typical of inland continental regions (Eurasia, North America), far from oceans, with extreme temperature fluctuations: very cold and long winters, warm and short summers, and low precipitation—the calculation of the necessary water for rainfed wheat can be performed using a simple seasonal calculation by growth phases [19]. During the autumn–winter period, for moisture accumulation:

$$S_b^{spring} = \min\left(S_{b,\max}, \sum A_t - \sum L_t\right) \quad (14)$$

During the spring–summer period, for water consumption:

$$S_b^{summer} = S_b^{spring} - \sum L_t \quad (15)$$

Additional water (moisture) received by the crop:

$$\Delta W_{crop} = \eta \sum L_t \quad (16)$$

Yield increase:

$$\Delta Y = k_y \, \Delta W_{crop} \quad (17)$$

Where k_y is the crop water-use efficiency coefficient, kg of grain per mm. To conduct actual field experiments in Uzbekistan, it is recommended to evaluate the following experimental parameters in three stages [20]:

Stage One: In laboratory conditions, determine the maximum water absorption (w_{max}), swelling rate (k_a), and water release rate upon drying (k_r) of bentonite granules.

Stage Two: Assess the actual portion of precipitation reaching the bentonite granule layer, how soil moisture changes with depth (0÷10, 10÷20, 20÷40 cm), and the rate of charging/discharging (absorption/release) of water by bentonite granules.

Stage Three: Adjust the mathematical model according to the seasonal dynamics of soil moisture, productive water storage, yield increase, and improvement of key quality characteristics of the crop [21].

To minimize the number of parameters required when constructing the mathematical model, it is sufficient to limit them to:

$S_{b,max}$ – maximum water storage of bentonite, mm;

k_a – water absorption rate;

k_r – water release rate;

θ_c – soil moisture threshold for the onset of active water release;

η – fraction of water available to plants;

β – mass fraction of bentonite in the soil layer.

Then the model can be expressed as follows:

$$\frac{dW}{dt} = I - ET - D - R + L - A \quad (18)$$

$$A = k_a I_b \left(1 - \frac{S_b}{S_{b,\max}}\right) \quad (19)$$

$$L = k_r \max\left(0, \frac{\theta_c - \theta}{\theta_c - \theta_{wp}}\right) S_b \quad (20)$$

$$\frac{dS_b}{dt} = A - L \quad (21)$$

The mathematical equations presented above are sufficient for constructing a preliminary conceptual model and obtaining experimental data on the use of bentonite as a water-retaining and water-accumulating element within the soil structure in the rainfed arid lands of Uzbekistan [22–25].

Conclusions.

Thus, to describe the hydrological role of bentonite in rainfed soils, a two-reservoir model was used, in which soil moisture is represented as the sum of matrix soil water and water associated with the bentonite component. The system dynamics are described by water balance equations for the root zone and the kinetics of water absorption/release by bentonite. The soil water retention curve is defined using the van Genuchten function, while the effect of bentonite is accounted for by an additional water retention function parameterized from laboratory data. This approach is consistent with published water retention models for soils and bentonites, as well as with field data showing increased field capacity and available water following bentonite application. The model allows for the preliminary assessment of water accumulation over the autumn–spring period, the duration of moisture retention in the root zone, the maximum water release by bentonite during crop growth, the optimal amount of bentonite to be applied to the soil, the effectiveness of this soil water retention method using bentonite, and the risk assessment of yield loss in dry years, among other applications.

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DESIGN AND IMPLEMENTATION OF AN AUTOMATED SMART FARM SYSTEM USING SOIL MOISTURE AND TEMPERATURE/HUMIDITY SENSORS

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Abstract. *This paper presents the design and experimental validation of a low-cost automated smart irrigation system based on the Arduino Uno platform. The system integrates a soil moisture sensor and a DHT11 to monitor environmental conditions and automatically control irrigation through a relay-driven water pump. Real-time environmental data are displayed on a 16×2 I2C LCD, and RGB LEDs provide visual feedback regarding soil conditions. The soil moisture threshold was experimentally set to 20% based on controlled drying observations. Experimental results demonstrate stable operation and an average system response time of approximately 1 second. This work represents the initial implementation phase of a scalable AIoT smart farm system, providing a foundation for future enhancements such as multi-sensor networks, wireless communication, and AI-based predictive irrigation. Notably, the system is particularly suitable for arid and semi-arid regions, such as much of Central Asia, where water scarcity and desertification pose significant challenges to sustainable agriculture.*

Keywords: *optimizing irrigation, resource waste, cloud systems, low-cost autonomous irrigation, smart farm systems.*

1. Introduction

Efficient water management is a critical challenge in arid and semi-arid regions, including Central Asia. Smart farming technologies based on embedded systems and environmental sensing offer practical solutions for optimizing irrigation and reducing resource waste. Recent research has focused on leveraging IoT and AI technologies for smart farm systems:

- In our previous work [1] demonstrated a basic AIoT system for environmental monitoring, highlighting the feasibility of low-cost sensor-based automation.
- Hasib et al. [2] proposed a cloud-connected smart plant monitoring system, integrating real-time sensing, automated alerts, and data analytics.
- Karar et al. [3] explored UAV-assisted smart irrigation with IoT-based cloud management, emphasizing remote monitoring and large-scale agricultural optimization.
- Rahman et al. [4] introduced IoT-based soil characterization techniques for crop-specific water management, showing the importance of precise soil data.
- Adkisson et al. [5] applied autoencoder-based anomaly detection for monitoring smart farming ecosystems, demonstrating the potential for AI-driven predictive maintenance in agriculture.

While these studies provide advanced solutions, many rely on cloud systems, UAVs, or AI models that are costly or require large-scale infrastructure. There is still a need for **low-cost, small-scale, locally deployable smart farm systems** that can operate autonomously while being scalable for future AIoT integration.

This paper addresses this gap by developing a **prototype Arduino-based smart farm system** that integrates soil moisture and temperature/humidity sensing with automatic irrigation. Unlike prior works, this study focuses on **practical implementation, low-cost hardware, and experimental validation**, forming the first step in a **series of AIoT smart farm research** aimed at scaling up with wireless connectivity, multi-sensor networks, and predictive irrigation.

The main contributions of this study are:

1. Development of a **low-cost autonomous irrigation control system**.
2. **Experimental validation** using real hardware implementation.
3. Demonstration of **scalability and potential for AIoT integration**.

2. System Architecture and Methodology

2.1 Hardware Components

The system consists of:

1. **Arduino UNO**: The microcontroller that manages the system and controls the sensors and actuators.
2. **Soil Moisture Sensor**: A sensor that measures the soil moisture level.
3. **DHT11 Temperature and Humidity Sensor**: A sensor that measures the ambient temperature and humidity.
4. **16x2 LCD Display (I2C)**: A display to show real-time soil moisture, temperature, and humidity data.
5. **RGB LED**: An LED used to display the current status of the soil moisture level (e.g., need water, dry, sufficient).
6. **Relay Module**: A module used to control the water pump.
7. **Water Pump**: Used to supply water to the soil when needed.

The relay module ensures safe isolation between low-voltage control circuitry and the external pump power supply.

2.2 Circuit Configuration

Component	**Arduino Pin**
Soil Moisture Sensor	A0
DHT11	7
LCD (I2C)	SDA: A4, SCL: A5
RGB LED	9, 10, 11
Relay Module	5

2.3 Control Algorithm

The block diagram of this system is shown below.

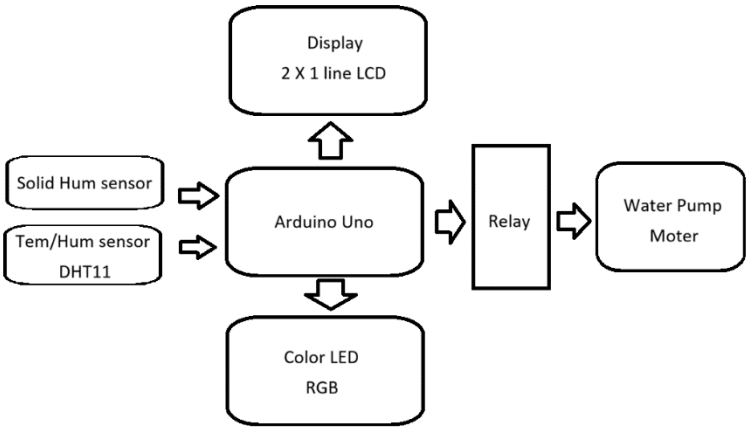


Figure 1. Block Diagram

The system operates as follows:

1. Acquire soil moisture analog value.
2. Convert raw value to percentage using calibration.
3. Acquire temperature and humidity from DHT11.
4. Display all values on LCD.
5. Compare soil moisture with threshold (20%).
6. Activate pump if moisture < 20%; deactivate otherwise.
7. Update RGB LED status:

- Purple (<20%)
- Yellow (20–50%)
- Green (>50%)

The 20% threshold was determined experimentally by observing soil drying conditions.

3. Experimental Setup

The complete hardware implementation of the proposed system is shown below.

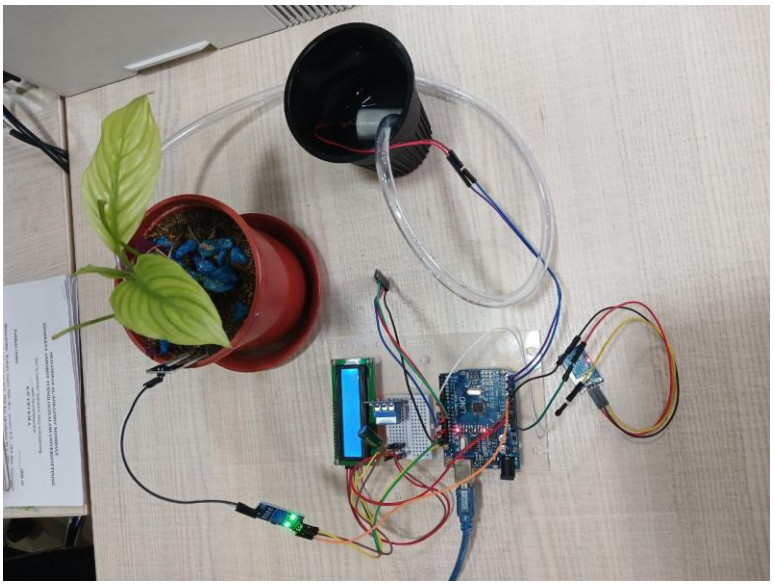


Figure 1. Overall Experimental Setup

Caption: The image shows the complete smart farm prototype including the soil moisture sensor inserted in the potted plant soil, the water pump with tubing for irrigation, the Arduino Uno board, the 16×2 LCD display, and RGB LED indicators. The wiring connects sensors, actuators, and control modules, illustrating the practical implementation of the system.

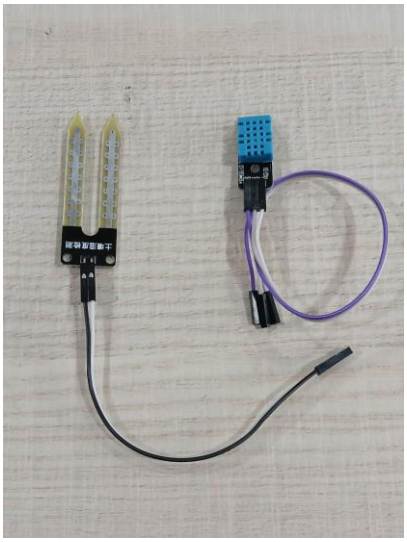


Figure 2. Sensor Modules

Caption: Soil moisture sensor and DHT11 temperature-humidity sensor used for environmental monitoring.



Figure 3. LCD Real-Time Display

Caption: Real-time soil moisture, temperature, and humidity data displayed on the 16×2 I2C LCD module.



Figure 4. RGB LED Status Indication

Caption: RGB LED color indication of soil moisture conditions.



Figure 5. Relay

Description: Used to isolate power between the Arduino device and the motor for safety



Figure 6. DC Water Pump

Caption: Pump drive motor for supplying water to plants

4. Experimental Results and Analysis

4.1 Performance Evaluation. The system was tested under varying soil moisture conditions. When soil moisture dropped below 20%, the relay activated the pump within approximately **1 second**, maintaining soil moisture above the threshold. Sensor readings were stable and responsive throughout the tests.

4.2 Sample Measurement Data

Soil Moisture (%)	Temperature (°C)	Humidity (%)
18	25.8	25.0
35	26.2	30.5
52	27.0	40.0
85	28.5	45.0

The results confirm effective closed-loop irrigation control.

5. Limitations

Current limitations include:

1. DHT11 sensor provides moderate measurement accuracy.

2. Single soil moisture sensor may not represent heterogeneous field conditions.
3. Standalone operation without remote monitoring.

Future enhancements will address these limitations with multi-sensor networks, wireless connectivity, and AI-based predictive irrigation.

6. Conclusion

This study demonstrated a **low-cost, small-scale smart farm system** based on the Arduino Uno. The system successfully automated irrigation using real-time soil moisture and environmental monitoring, providing:

- Rapid and reliable response (~1 second)
- Visual feedback via RGB LEDs
- Real-time data display on LCD

The proposed system is especially applicable to arid regions, including Central Asia, offering a practical solution to water scarcity and supporting sustainable agriculture in areas prone to desertification. This work establishes the first phase of a scalable AIoT smart farm research series, providing a practical foundation for future integration of wireless communication, multi-sensor networks, and AI-based predictive control.

7. Future Work

Planned extensions include:

1. Integration of Wi-Fi modules (ESP8266 / ESP32) for remote monitoring and control.
2. Multi-sensor distributed architecture for large-scale fields.
3. AI-based predictive irrigation models for optimized water use.
4. Cloud-based data storage and real-time visualization.
5. Field deployment for efficiency analysis in real agricultural environments.

These enhancements will enable the proposed system to evolve into a fully AIoT-enabled smart farm, forming subsequent papers in this research series.

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PREDICTIVE MAINTENANCE MODEL BASED ON INDUSTRIAL IoT IN THE AUTOMOTIVE INDUSTRY

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Abstract. *The increasing complexity of production systems in the automotive industry makes ensuring equipment reliability a strategic technological challenge. This article is aimed at developing a Predictive Maintenance (PM) model based on Industrial Internet of Things (IIoT) technologies and machine learning algorithms. The integration of sensor data and real-time monitoring systems enables optimization of production processes and improves the efficiency of maintenance management. In the context of global industrial transformation, digital manufacturing technologies play an important role in increasing production efficiency. According to the World Economic Forum, the implementation of Industry 4.0 technologies significantly increases global industrial productivity [1].*

Keywords: *industrial IoT, Predictive Maintenance (PM), Machine Learning, Smart Manufacturing.*

Introduction

The introduction of digital technologies is considered an important strategic factor in the development of modern industrial systems. Within the framework of the concept of the Fourth Industrial Revolution, Industrial IoT (IIoT), artificial intelligence, big data analytics and Digital Twin technologies are transferring production systems to a cyber-physical architecture. Based on IIoT, it is possible to collect, transmit and analyze data from equipment in real time, which increases the transparency and accuracy of management of production processes.

The concept of Predictive Maintenance (PM) is an important component of this transformation, which involves forecasting the technical condition of equipment based on sensor data and proactively managing maintenance. Unlike traditional reactive or strictly planned maintenance, PM predicts the probability of failure in advance through data-based predictive models and reduces the number of unplanned downtime. As a result, the OEE (Overall Equipment Effectiveness) indicator increases, operating costs are optimized and production stability is ensured.

The automotive industry is a complex production system based on high precision, tact and synchronized operations. Sudden equipment failure on welding, body assembly, painting and final assembly lines can lead to the shutdown of the entire conveyor system. Equipment degradation (vibration fatigue, thermal overload, mechanical wear) directly affects production efficiency. Therefore, the introduction of Predictive Maintenance (PM) systems is of strategic importance in the automotive industry. The issue of modernization and digitalization of the Uzbek industry has risen to the level of state policy. Shavkat Mirziyoyev, in his Address to the Oliy Majlis, emphasized the need to digitize economic sectors, introduce modern management systems in production and increase efficiency based on innovative technologies [2]. Also, the "Digital Uzbekistan – 2030"

strategy sets the widespread implementation of digital technologies in industrial enterprises and automation of production processes as a priority task [3]. The Development Strategy for 2022–2026 notes the need to expand the production of high-value-added industrial products and introduce innovative management technologies [4].

In this regard, the development of a Predictive Maintenance (PM) model based on Industrial IoT in the automotive industry and its integration into the production system is of not only technological but also strategic and economic importance. This direction will serve to ensure the stability of production, increase global competitiveness, and promote the innovative development of the national industry..

Practical experiences on the topic

The effectiveness of Industrial IoT and predictive maintenance technologies is confirmed by the experience of leading industrial enterprises in the world. In particular, automotive and high-tech manufacturing enterprises are achieving optimization of technical maintenance, increasing equipment reliability, and ensuring the continuity of production processes based on digital technologies. For example, BMW Group has implemented virtual modeling systems for production processes as part of the digital factory concept. This system allows for pre-simulation of production processes and optimization of planning processes. According to the company: “The virtual factory planning tool integrates a range of planning data and applications and allows real-time collaboration with unrestricted compatibility” [5].

Also, the Amberg Electronics Plant of Siemens AG is one of the successful examples of digital production technologies. Industrial IoT, automated monitoring, and production data analysis systems are widely used at this enterprise. As a result, product quality has been brought to a very high level. The company’s representatives state: “We have a defect rate of just 11 defects per million. That’s 99.9989 percent perfection” [6].

General Motors also has experience in using predictive maintenance technologies in the automotive industry. The company is developing systems for real-time monitoring of equipment status and early detection of technical failures by implementing IoT sensor networks on production lines. Studies note: “Predictive maintenance uses connected sensors and advanced analytics to detect anomalies and predict equipment failures before they occur” [7]. Bosch’s Bosch Connected Industry platform is also expanding the possibilities of forecasting technical maintenance based on IoT in the industry. Studies note: “The intelligent use of vast condition data enables not only preventive but also predictive maintenance and changes the strategy from troubleshooting to error prevention” [8].

Predictive maintenance technologies based on Industrial IoT are also being actively used in the aviation industry. In particular, Airbus has implemented a system for early detection of technical failures based on real-time data and analytical systems. Studies have noted: “Predictive maintenance uses real-time data and advanced analytics to anticipate failures before they occur and optimize maintenance operations” [9].

These experiences show that the implementation of predictive maintenance technologies based on Industrial IoT is of great importance in increasing the reliability of equipment operation, reducing production downtime, and optimizing maintenance costs.

Implementation model at “UzAuto Motors” JSC

The implementation of a Predictive Maintenance (PM) system at UzAuto Motors is proposed to be carried out in accordance with the company’s digital transformation strategy of the automotive manufacturing system. The model is based on a three-stage technological paradigm.

First stage – pilot testing phase (Body Shop Lines). The pilot project will be implemented within the welding and body assembly technological processes (Body Shop). At this stage, Industrial Internet of Things (IIoT) sensor systems will be installed to monitor the operational condition of robotic welding equipment. Parameters such as vibration amplitude, temperature regime, electrical current load, and mechanical vibration frequency will be monitored in real time.

Using feature extraction methods from sensor data, degradation trends will be identified, and the probability of equipment failure will be predicted using machine learning algorithms. Testing of the PM diagnostic model in Body Shop lines serves as a scientific and technical basis for assessing the technical effectiveness of the Industrial IoT platform, calibrating the accuracy of the model, and algorithmic optimization.

Second stage – technological expansion (Paint Shop Lines)

Based on the results of the pilot phase, the introduction of PM monitoring systems into the technological processes of the Paint Shop is planned. To ensure the stability of painting quality, the following technological parameters will be monitored:

- air temperature and humidity levels;
- pressure differential;
- concentration of chemical components;
- thermodynamic regime of drying chambers;
- dynamics of material viscosity.

At this stage, probabilistic forecasting algorithms and regression-based machine learning models will be applied to evaluate the risk of technological environment degradation in real time.

Third Stage – Enterprise-Level Integration Platform

It is recommended to expand the PM platform to the enterprise’s core production systems.

At this stage, integration with the following industrial information systems will be implemented:

- Manufacturing Execution System (MES);
- Supervisory Control and Data Acquisition (SCADA);
- Industrial IoT data lake architecture;
- Machine Learning analytical module;
- Real-time decision support platform.

The integrated digital management architecture will increase the level of production process observability, reduce technological risks, and optimize operational efficiency. The proposed model will contribute to increasing the level of cyber-physical control integration within automotive production lines.

Discussion

Predictive Maintenance (PM) systems based on Industrial Internet of Things form an adaptive and data-driven model for managing production processes in modern industrial enterprises. These systems enable the collection and analysis of numerous technological indicators—such as equipment operating parameters, vibration, temperature, pressure, and electrical energy consumption—in real time through Internet of Things sensors. As a result, continuous monitoring of the technical condition of production systems becomes possible, allowing early detection of potential equipment failures.

In Predictive Maintenance systems, Machine Learning algorithms play a crucial role. In particular, classification models help identify potential malfunctions by categorizing equipment operating states into different conditions.

At the same time, the Probabilistic Forecasting approach makes it possible to estimate the probability of failures that may occur during equipment operation and to optimally schedule maintenance activities. This enables the transition of production systems from a reactive management model to a proactive management model. The implementation of PM systems based on Industrial IoT can lead to several significant technological and economic outcomes in industrial enterprises. In particular:

- the reliability of equipment operation increases and the stability of technological processes is ensured;
- unplanned downtime in production lines is significantly reduced;
- operational costs decrease due to the optimization of maintenance processes;
- efficiency in the use of energy resources improves;
- the overall efficiency and sustainability of production processes are strengthened.

At the same time, several important challenges arise in implementing Predictive Maintenance systems, including ensuring the quality of collected data, processing large volumes of sensor data, and integrating analytical models into existing production systems. Considering these factors, the comprehensive integration of Industrial IoT and Artificial Intelligence technologies can significantly accelerate the digital transformation of industrial enterprises.

Conclusion

In the automotive industry, the integration of Industrial Internet of Things, large-scale production data analytics, and Machine Learning technologies represents one of the key technological components of the Smart Manufacturing paradigm. These technologies enable digital monitoring of production processes, allowing real-time assessment of equipment conditions and early detection of potential failures.

The Predictive Maintenance (PM) model developed on the basis of Industrial IoT contributes to increasing the level of digital transformation in production systems, optimizing maintenance processes, and ensuring the reliability of equipment operation. This approach enables the prediction of equipment failures in advance, which helps reduce unplanned downtime, increase production efficiency, and lower maintenance costs. At the same time, the large volume of data collected through Internet of Things sensors serves as an important source of information for deep analysis of production system conditions and for improving digital management mechanisms.

The research results indicate that the implementation of predictive maintenance technologies based on Industrial IoT plays a significant role in ensuring the stability of production processes in the automotive industry and in increasing the technological competitiveness of industrial enterprises.

In future research, it is advisable to further develop Deep Learning-based fault prediction models, feature extraction methods aimed at deep analysis of signal data, and adaptive diagnostic algorithms operating in real time. In addition, integrating Industrial IoT platforms with Digital Twin technologies could enable virtual modeling of production systems and further improve predictive maintenance processes.

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MODELING THE STEAM GENERATION PROCESS IN EVAPORATION UNITS OF THE OIL AND GAS INDUSTRY

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Abstract. *Evaporation units are an important component of technological processes in industrial enterprises. They are widely used for concentrating solutions, removing excess moisture, and improving product quality. In particular, evaporation apparatuses play a crucial role as heat exchange equipment in the chemical, food, and oil and gas industries. Therefore, in-depth study of the evaporation process, development of its mathematical model, and optimal control of process parameters are considered important scientific and practical tasks. In this research, the issue of mathematical modeling of the steam preparation process in industrial evaporation units is examined. A system of differential equations based on material and heat balance equations was developed to describe the process. The obtained mathematical model makes it possible to analyze the dynamic characteristics of the technological object and determine the time variation of process parameters. The modeling process was implemented using the Simulink visual modeling environment. Based on the results, the patterns of changes in product concentration and enthalpy over time during the evaporation process were determined. The results of the study are important for effective control of industrial evaporation units, improving energy efficiency, and optimizing technological processes.*

Keywords: *evaporation process, mathematical modeling, material balance, heat balance, Simulink, concentration, enthalpy, dynamic model.*

1. Introduction

In industrial enterprises, the evaporation process plays an important role in concentrating solutions, removing excess water from liquids, and processing various technological products. According to the Decree of the President of the Republic of Uzbekistan dated September 11, 2023, No. PF-158 "On the Strategy 'Uzbekistan – 2030,'" several important tasks have been defined to ensure the continuous supply of necessary energy resources to economic sectors and the population [1]. In particular, these tasks include increasing the amount of electricity supplied to economic sectors and the population to 120 billion kWh, increasing natural gas production to 62 billion cubic meters, doubling the energy efficiency of economic sectors, and modernizing the infrastructure for the distribution, generation, and delivery of electricity and natural gas to consumers. \

The implementation of these tasks is partly dependent on the efficiency of evaporation processes in the energy sector, which is influenced by the design characteristics of the equipment, heat transfer conditions, and the optimal control of technological parameters. Evaporation units are widely used in the chemical and oil and gas industries, where they enable modification of product composition and achievement of the required concentration. In order to effectively organize and control the evaporation process, it is essential to develop a mathematical model of this technological system [2,3]. Mathematical modeling makes it possible to conduct an in-depth theoretical analysis of the process, determine its static and dynamic characteristics, and develop optimal control algorithms. Furthermore, in evaporation units operating under vacuum conditions,

the boiling temperature of the solution can be reduced, which helps preserve heat-sensitive substances and improve product quality.

2. Literature Review

Issues related to the modeling of evaporation processes and the improvement of energy efficiency have been studied in numerous scientific works [4–7]. In a study devoted to the mathematical modeling of multiple-effect evaporation units and the evaluation of their energy efficiency, the main technological parameters of the evaporation process were identified and the possibilities of reducing energy consumption were analyzed (Kaya et al., 2007).A mathematical model of a multiple-effect evaporation unit used at an industrial scale was developed, and the influence of technological parameters on process efficiency and product quality in the production of tomato concentrate was investigated (Miranda et al., 2005).

A mathematical model based on lumped parameters was developed to describe the heat transfer processes occurring in the evaporator section of a heat pump, and the operating characteristics of the device were analyzed (Nyers et al., 2014). In addition, a mathematical model of a counter-current multiple-effect evaporation system used for fruit juice concentration was developed, and the influence of technological parameters on process performance and energy efficiency was analyzed (Ruan et al., 2015).

3. Research Methodology

In this study, the mathematical modeling method was used to investigate the steam generation process in industrial evaporation units. To describe the process, a mathematical model based on material and heat balance equations was developed. A system of differential equations was formulated to represent the static and dynamic states of the evaporation process. The main parameters analyzed included the mass of the product, its concentration, and the change in enthalpy over time.

Based on the developed mathematical model, computer simulation of the process was carried out using the Simulink visual modeling environment. In the software environment, a functional block diagram of the process was constructed. Using the developed model, the dynamic characteristics of the evaporation process and the patterns of change in the main parameters were studied.

4–5. Analysis and Results

In the mathematical modeling of the evaporation process, analytical approaches are applied, taking into account the physicochemical phenomena occurring during the process, the properties of the processed mixture, as well as the structural parameters of the equipment. This approach requires a thorough theoretical analysis of the process and the development of equations describing the operation of the equipment under static and dynamic operating conditions.

In the oil and gas industry, evaporation units are widely used as heat transfer equipment. In devices operating under vacuum conditions, the secondary vapor generated during the evaporation process is condensed through a special condenser, while the remaining gases are removed using a pump [8]. This method significantly reduces the boiling temperature of the solution, which prevents the degradation of heat-sensitive substances and preserves product quality.

Furthermore, the use of a vacuum system provides several advantages:

- increases the energy efficiency of the evaporation process;
- enhances the temperature difference, which improves heat transfer efficiency;

- helps optimize the heat transfer surfaces of the equipment and reduce metal consumption.

In mathematical modeling of the evaporation process, the fundamental equations are the material and heat balance equations. The material balance equation in the static state expresses the mass equilibrium in the evaporation apparatus and mathematically determines the relationship between the inlet and outlet flows in the process.

$$S_0 = S_k + W \quad (1)$$

where S_0 – the feed extract supplied to the evaporator, kg/h; W – the rate of evaporated water, kg/h; S_k – the flow rate of the concentrated extract, kg/h.

To derive the dynamic material balance equation, a variable m (kg) was introduced to represent the mass of the extract in the evaporator and the possible material losses within the apparatus. In this case, the material balance can be expressed in the form of a dynamic equation.

$$\frac{dm}{dt} = S_0 - S_k - W \qquad (2)$$

In the technological process, since the change in the concentration of the evaporating product is described by a dynamic equation, a variable b was introduced to represent the time-dependent concentration. The dynamic behavior of the concentration change is expressed in the following equation.

$$\frac{db}{dt} = \frac{S_0 \cdot (b_0 - b) - W \cdot b}{m} \qquad (3)$$

In the evaporation process, in order to describe the dynamic behavior of the heat balance, it is necessary to know the heat supplied to the unit, the heat losses, and the enthalpy of the process under stationary operating conditions.

$$\frac{dh}{dt} = \frac{S_0 \cdot (h_0 - h) - W \cdot (i - h) + Q - L}{b} \qquad (4)$$

where h_0 – the initial enthalpy of the evaporating product, J/kg; i – the enthalpy of the secondary vapor, J/kg; Q – the heat supplied to the evaporator body, J/h; Q – the heat loss in the evaporator body, J/h.

The obtained system of differential equations makes it possible to model the dynamics of the evaporation process in a single body of the evaporation unit [9–12]. The modeling scheme of this technological process was developed using the Simulink visual modeling software package (shown in Figure 9). For the constructed scheme to function correctly, all blocks must be properly connected, and the corresponding parameters and coefficients must be specified.

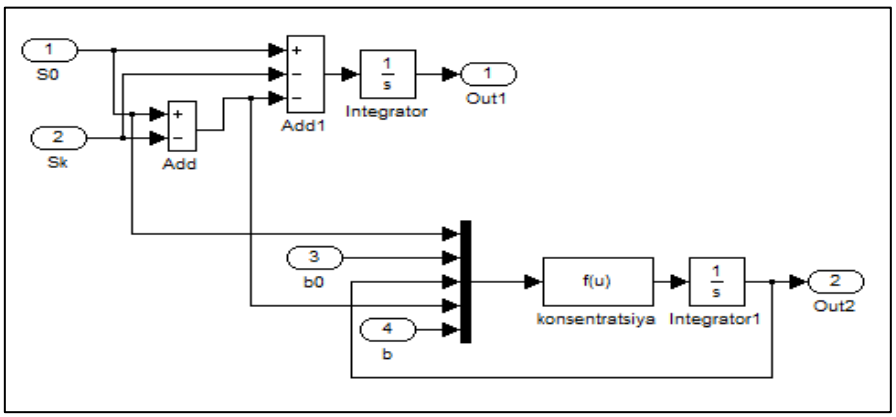


Figure 1. Model of the process in the Simulink package.

The presented modeling scheme is used to simulate the process when the initial data are provided.

The following graphs show the changes in concentration and enthalpy values (Figure 2).

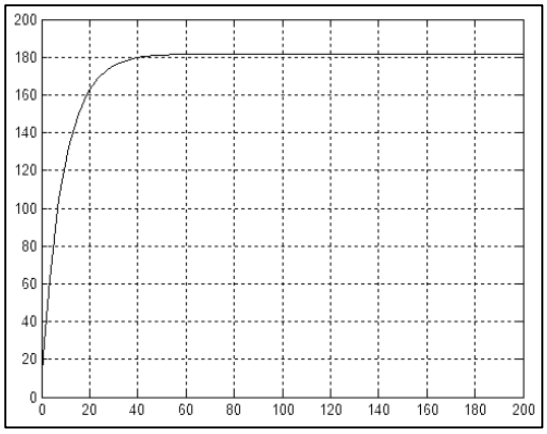


Figure 2. Change in the concentration value of the evaporating product.

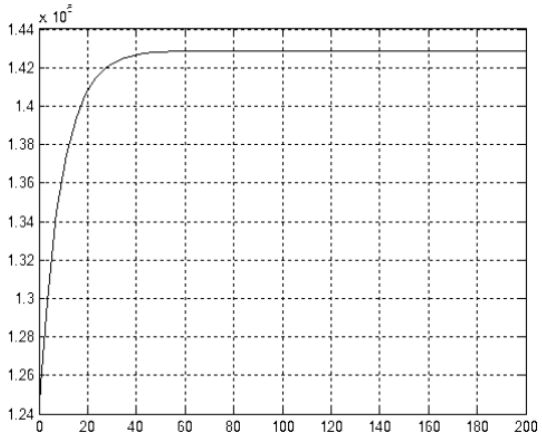


Figure 3. Change in the enthalpy value of the evaporating product.

To effectively automate the evaporation process and develop an optimal control system, it is necessary to model the technological object using an analytical approach. This process is based on a thorough analysis of the technological system, identification of controllable parameters, and the formation of control algorithms based on mathematical models.

6. Conclusion and Recommendations

In this research, the issue of mathematical modeling of the steam generation process in industrial evaporation units was investigated. During the study, a mathematical model based on material and heat balance equations was developed to describe the evaporation process. A system of differential equations representing the static and dynamic states of the process was formulated, and the time-dependent changes of technological parameters were analyzed.

Using the Simulink visual modeling environment, a functional model of the process was constructed, and the dynamics of changes in the concentration and enthalpy of the evaporating product were obtained in graphical form. The obtained results make it possible to analyze the technological characteristics of the evaporation process more deeply and ensure more efficient control of the process.

Based on the research results, the following recommendations are proposed:

- to widely use mathematical modeling methods to optimize the operating modes of industrial evaporation units;

- to reduce energy consumption by controlling the evaporation process through automated control systems;
- to improve vacuum evaporation systems in order to increase the efficiency of heat transfer processes;
- to apply the developed mathematical model in the design and modernization of technological processes.

The results of this study are important for improving the efficiency of industrial evaporation units, ensuring rational use of energy resources, and enhancing technological processes.

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DESIGN AND DEVELOPMENT OF A MYOWARE EMG SENSOR-BASED SYSTEM FOR MUSCLE ACTIVITY MONITORING ON A CLOUD PLATFORM

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Abstract. *This article examines the development of a system for determining muscle activity levels based on the Myo Ware EMG sensor and enabling their remote monitoring through a cloud platform. The study investigates the process of acquiring electromyographic (EMG) signals generated by muscle activity, processing them using a microcontroller, and transmitting them to a cloud platform. In the proposed system, an analog signal is obtained from the muscle using the Myo Ware EMG sensor and digitized by the ESP32 microcontroller. The acquired signal is then transmitted to the ThingSpeak cloud platform via a GSM module, where it is visualized in both graphical and numerical forms. As a result of the research, it became possible to determine the level of muscle activity based on the signal amplitude and its variations. The proposed system enables near real-time monitoring of muscle activity, remote analysis of collected data, and monitoring of patients' physical conditions. This system can be applied in medicine, rehabilitation processes, and remote healthcare monitoring systems.*

Keywords: *muscle activity, EMG signals, millivolt level, rehabilitation systems, GPS functionality, signal behavior.*

Introduction

In recent years, the need for technologies that enable remote monitoring of physiological processes in the human body has been increasing in the medical field. In particular, the study of muscle activity plays an important role in rehabilitation, sports medicine, and biomedical engineering. The electrical activity of muscles can be detected using the electromyography (EMG) method. EMG signals are bioelectrical signals generated as a result of muscle fiber contractions, and they provide valuable information for assessing the level of muscle activity. One of the modern devices used for measuring EMG signals is the Myo Ware EMG sensor. This sensor allows the measurement of electromyographic signals obtained from muscles and enables their processing using microcontrollers. At the same time, the development of IoT technologies has made it possible to remotely monitor medical systems through cloud platforms.

In this article, a system for remote monitoring of muscle activity is proposed. The system is based on acquiring muscle signals using the Myo Ware EMG sensor, processing them with an ESP32 microcontroller, and transmitting them to the ThingSpeak cloud platform using a GSM

communication module. The proposed system allows the visualization of muscle activity in graphical and numerical formats and provides the ability to monitor the collected data remotely.

Main components of the device and their functions

The proposed muscle activity monitoring system consists of several main hardware components, including the Myo Ware EMG sensor, the ESP32 microcontroller, the A9G GSM module, and a battery used as the power supply. These components are integrated to perform the processes of acquiring muscle signals, processing them, and transmitting the data to a cloud platform. The main objective of the system is to monitor muscle activity in near real-time and provide the capability for remote observation and analysis of the collected data.

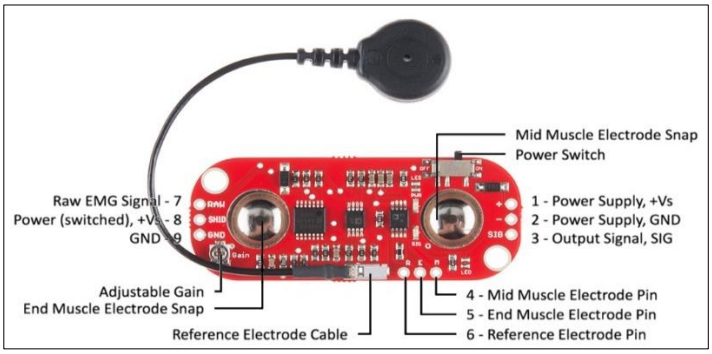


Figure 1. Myo Ware EMG sensor

The Myo Ware EMG sensor is a specialized biosensor designed to measure electromyographic (EMG) signals generated by muscle activity. This sensor detects bioelectrical signals produced as a result of muscle fiber contractions and outputs them in the form of an analog electrical signal. EMG signals usually have very small amplitudes, typically at the millivolt level. Therefore, the Myo Ware sensor includes built-in signal amplification (amplifier) and noise-reduction filtering circuits. These components allow the muscle signal to be acquired more accurately and with greater stability.

The sensor typically operates using special electrodes that are placed on the surface of the muscle. These electrodes detect the electrical activity generated when the muscle contracts. The analog signal obtained from the Myo Ware sensor is then received by a microcontroller and converted into digital form for further processing. The advantages of this sensor include its compact size, low cost, ease of use, and the ability to acquire signals in real time. For these reasons, the Myo Ware sensor is widely used in fields such as biomedical engineering, sports monitoring, rehabilitation systems, and human – machine interface applications.

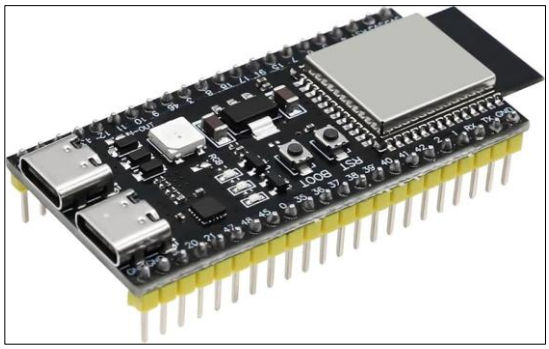


Figure 2. ESP32 microcontroller

The ESP32 microcontroller serves as the main control and computing unit of the system. This microcontroller receives the analog signal coming from the Myo Ware EMG sensor and converts it into digital form using its built-in analog-to-digital converter (ADC). The digitized

signal is then processed using software algorithms and used to determine the level of muscle activity. The ESP32 microcontroller is distinguished by its high processing speed, low power consumption, and support for multiple peripheral interfaces. Due to its integrated Wi-Fi and Bluetooth modules, it is widely used in IoT-based systems. In this study, the ESP32 microcontroller is responsible for collecting data from the sensors, performing preliminary signal processing, calculating the level of muscle activity, and transmitting the processed data to the cloud platform via the GSM module.

In addition, the ESP32 microcontroller enables signal analysis, monitoring of signal variations over time, and calculation of various mathematical indicators. For this reason, it is considered one of the modern microcontrollers widely used in medical monitoring systems and IoT devices.

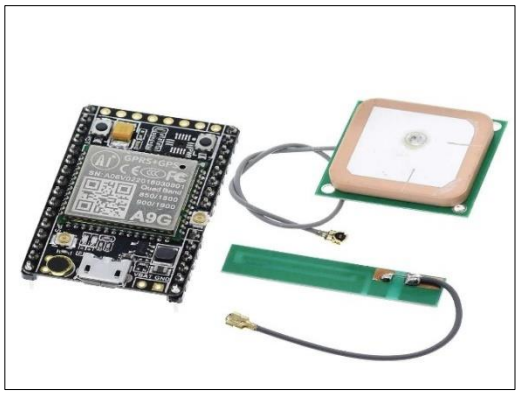


Figure 3. A9G GSM moduli

The A9G GSM module is a communication module designed to transmit data through wireless communication networks. This module uses GSM and GPRS technologies to send data obtained from the device to the internet via a mobile communication network. The A9G module communicates with the ESP32 microcontroller through a serial communication interface (UART) and transmits the data received from the microcontroller to the cloud platform. In the proposed system, muscle activity data obtained from EMG signals are transmitted to the ThingSpeak cloud platform through the A9G module. On the cloud platform, these data are stored and visualized in both graphical and numerical forms, allowing users to monitor them remotely. The use of the GSM module enables the system to operate independently of Wi-Fi networks, which provides significant advantages for remote monitoring systems. In addition, the A9G module also supports GPS functionality, which makes it possible to determine the geographical location of the device when necessary. For this reason, it is widely used in various IoT systems, especially in remote monitoring and tracking applications.



Figure 4. Battery for the device

The battery serves as the main power source that provides energy for the operation of the device. It supplies the electrical power required for the Myo Ware EMG sensor, ESP32 microcontroller, and A9G GSM module. The use of a battery ensures that the device remains portable and allows it to operate in various environments. As a power source, rechargeable lithium-ion or lithium-polymer batteries are typically used. These batteries are compact in size and capable of supporting the device's operation for extended periods. By using a battery, the device can operate wirelessly and independently, enabling the monitoring of a patient's muscle activity even during movement.

The use of a portable power supply allows the monitoring system to function in a mobile mode. As a result, muscle activity can be monitored not only in laboratory conditions but also in real-life scenarios such as during rehabilitation processes or everyday activities.

System architecture and block diagram

The proposed muscle activity monitoring system operates based on the integration of several hardware and software components. The main objective of the system is to acquire electromyographic signals generated by muscle activity, process them, and transmit them to a cloud platform for remote monitoring. The system architecture consists of the following main modules:

1. MyoWare EMG sensor
2. ESP32 microcontroller
3. A9G GSM communication module
4. ThingSpeak cloud platform
5. User monitoring interface

The operation of the system is performed as follows. Initially, the MyoWare EMG sensor receives bioelectrical signals generated by muscle activity through electrodes attached to the muscle surface. These signals are analog in nature and are processed through amplification and filtering circuits integrated within the sensor. In the next stage, the analog signal is received by the analog-to-digital converter (ADC) of the ESP32 microcontroller and converted into digital form. The ESP32 microcontroller performs preliminary signal processing, determines the level of muscle activity, and prepares the data for transmission.

The processed data are then transmitted to the internet through the A9G GSM module using a mobile communication network. The transmitted data are sent to the ThingSpeak cloud platform, where they are stored. On the ThingSpeak platform, the received data are visualized in graphical and numerical formats. Users can access the platform through the internet and remotely monitor muscle activity information. This system can be applied in remote medical monitoring systems, rehabilitation processes, and sports activity monitoring. The block diagram of the system can be represented in the following sequence:

Stage	System Component	Function
1	Muscle Activity	Bioelectrical EMG signals are generated as a result of human muscle contraction.
2	Myo Ware EMG Sensor	Measures the EMG signal generated by the muscles and outputs it as an analog signal.
3	ESP32 Microcontroller (ADC and Signal Processing)	Converts the analog EMG signal into digital form using ADC, performs initial signal processing, and prepares the data.

4	A9G GSM Module	Transmits the data received from the ESP32 to the internet via GSM/GPRS.
5	Internet Network	Transfers the data sent from the device to the cloud platform.
6	ThingSpeak Cloud Platform	Receives, stores, and processes EMG signal data.

Algorithm for acquiring emg signals and transmitting them to the Thingspeak cloud platform

In the proposed monitoring system, the process of acquiring muscle signals, processing them, and transmitting them to the cloud platform is performed based on a specific algorithm. This algorithm is designed to ensure stable operation of the device and enable remote monitoring of the collected data. The operation of the algorithm consists of the following stages:

Step 1. System Initialization

In the first stage, the ESP32 microcontroller is powered on and all devices are initialized. During this stage, the Myo Ware sensor, A9G GSM module, and other interfaces are configured and prepared for operation.

Step 2. EMG Signal Acquisition

The Myo Ware EMG sensor receives electromyographic signals generated by muscle activity through electrodes placed on the muscle surface. These signals are analog in nature and are read by the ADC module of the ESP32 microcontroller.

Step 3. Signal Processing

The ESP32 microcontroller processes the digitized signal obtained from the sensor. At this stage, the amplitude of the signal is determined and the level of muscle activity is evaluated. If necessary, additional mathematical operations such as signal smoothing or averaging can also be applied.

Step 4. Data Preparation

The processed signal is converted into a specific format suitable for transmission. The data are prepared in formats such as JSON or HTTP request format for sending to the cloud platform.

Step 5. Data Transmission

The ESP32 microcontroller transmits the prepared data through the A9G GSM module to the mobile communication network. The GSM module establishes an internet connection and sends the data to the ThingSpeak platform server.

Step 6. Cloud Storage and Visualization

The data transmitted to the ThingSpeak platform are stored on the server and automatically visualized in graphical and numerical forms. Users can access the platform via the internet and monitor muscle activity data in near real time.

Using this algorithm, continuous monitoring of muscle activity is achieved, and the acquired EMG signals can be remotely observed through the cloud platform.

The figure shows a prototype device developed to measure electromyography (EMG) signals generated by muscle activity. The device consists of electronic components placed inside a protective enclosure and uses a Myo Ware EMG sensor to detect bioelectrical signals produced by muscle contractions. The sensor is connected to the human body through electrodes, which capture electrical signals generated when muscles contract or relax. The upper part of the device contains the main electronic module housed inside the enclosure, which typically includes a

microcontroller and power management components. A power switch is integrated into the casing to allow the device to be turned on and off easily. The lower part of the system contains the Myo Ware EMG sensor board and electrode connectors used for acquiring muscle signals.

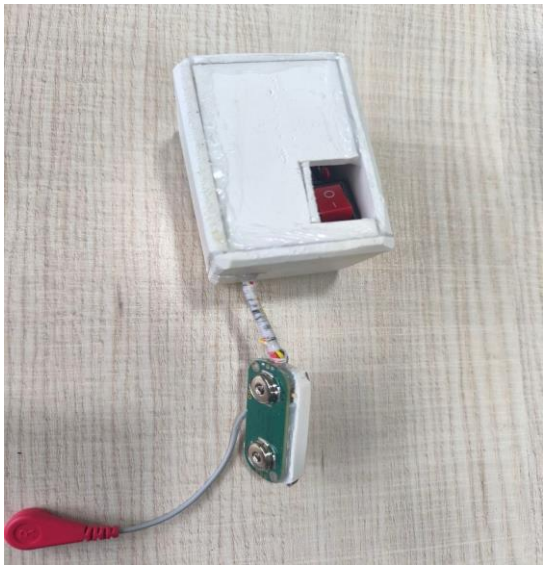


Figure 5. Prototype of a muscle signal measurement device based on the Myo ware EMG sensor.

The device can be integrated with IoT technologies to transmit collected EMG signals wirelessly to a remote server or cloud platform. This enables real-time monitoring, storage, and analysis of muscle activity data. Such systems are widely used in biomedical engineering, healthcare monitoring, rehabilitation systems, sports science, and physiological signal research.

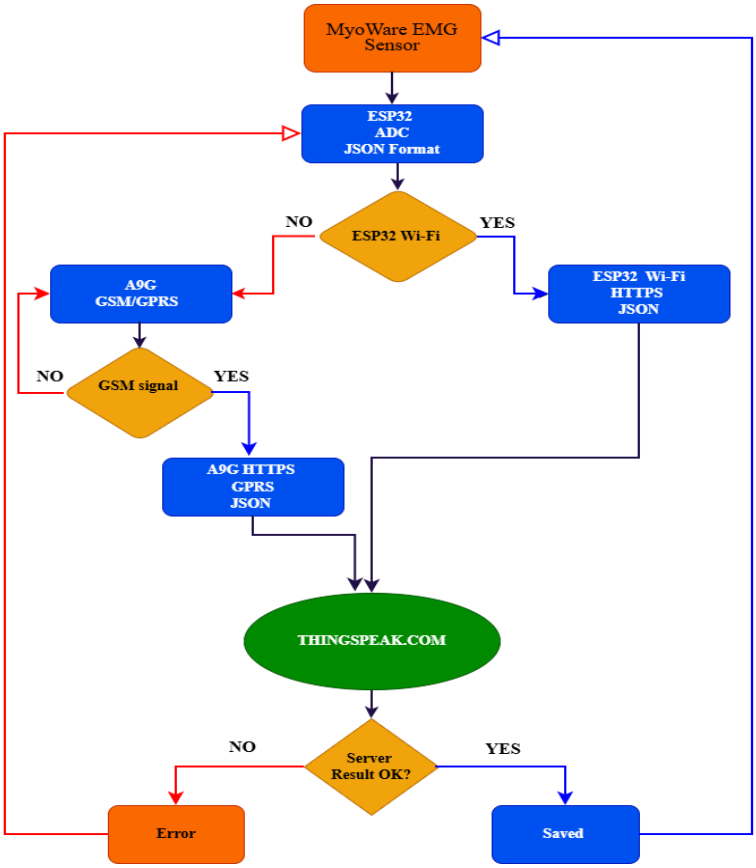


Figure 6. Algorithm for transmitting EMG signals to the Thingspeak cloud platform using Myo ware EMG sensor, ESP32, and A9G GSm module

This algorithm illustrates the process of remote muscle activity monitoring using EMG (Electromyography) signals through IoT technology and cloud platforms. The process begins with the Myo Ware EMG sensor, which captures bioelectrical signals generated by muscle activity. The analog EMG signal is then processed by the ESP32 microcontroller, where it is converted into digital data using an ADC (Analog-to-Digital Converter) and formatted into JSON. In the next stage, the data can be transmitted to the internet using two communication methods. The first method uses the ESP32 Wi-Fi module, which sends the data directly to the cloud platform via the HTTPS protocol in JSON format. The second method uses the A9G GSM/GPRS module, which transmits the data through the mobile cellular network. If a GSM signal is available, the A9G module sends the data to the cloud server using HTTPS in JSON format.

Once the data reaches the ThingSpeak.com cloud platform, the server receives and processes it. If the server successfully receives the data, it is stored in the system and marked as Saved, allowing it to be used later for graphical and numerical monitoring. If an error occurs during transmission, the system returns an Error status, indicating that the data transmission failed and may need to be resent.

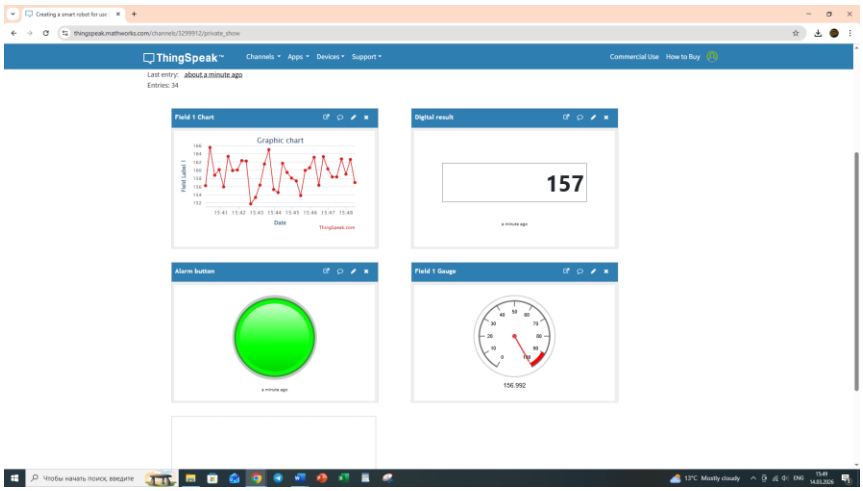


Figure 7. Real-time visualization interface of EMG signal data on the Thingspeak cloud platform.

The figure illustrates the real-time monitoring interface of EMG (Electromyography) signal data on the ThingSpeak cloud platform. In this system, the EMG signal collected from the Myo Ware EMG sensor is transmitted through the ESP32 microcontroller to the cloud server using an internet connection. Once the data reaches the ThingSpeak platform, it is automatically stored and visualized for monitoring and analysis. The interface includes several visualization components that help users observe the signal behavior in real time. The graphical chart displays the variation of the EMG signal over time, allowing users to analyze the dynamic changes in muscle activity. The digital result panel shows the current numerical value of the signal, providing a quick and clear representation of the latest measurement.

In addition, the gauge indicator visually represents the signal magnitude within a predefined range, making it easier to interpret the signal level. The system may also include status indicators or alarm buttons, which can be used to signal abnormal conditions or alert users when the signal exceeds certain thresholds. By integrating IoT communication and cloud computing technologies, this monitoring interface enables remote observation, storage, and analysis of physiological signals. Such systems are useful in medical monitoring, rehabilitation, sports science, and biomedical research, where continuous tracking of muscle activity is required. The

use of cloud platforms like ThingSpeak also allows researchers and healthcare professionals to access data from anywhere, improving the efficiency and scalability of physiological signal monitoring systems.

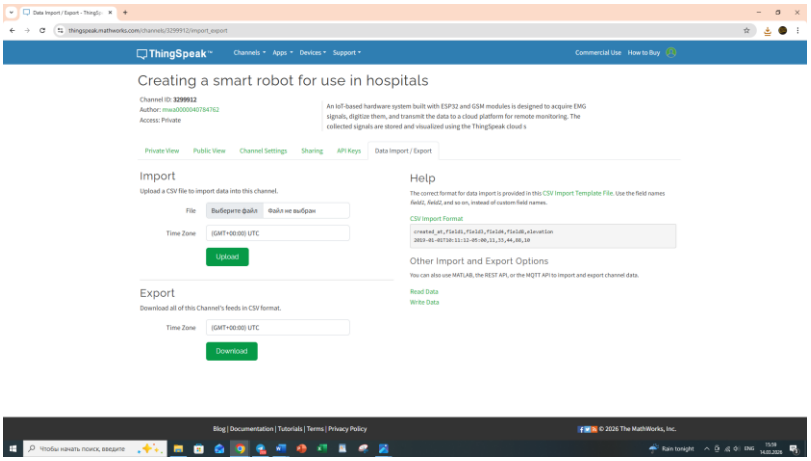


Figure 8. Data import and export interface of the Thingspeak cloud platform

The figure shows the Data Import/Export interface of the ThingSpeak cloud platform. This section allows users to upload data to the channel in CSV format or download stored channel data for further analysis. The import function enables users to upload datasets from external devices or systems, while the export function allows downloading all stored data from the channel in CSV format.

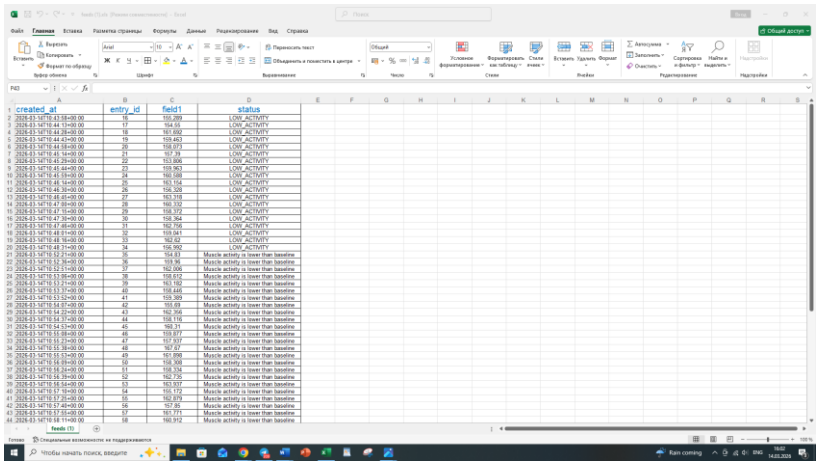


Figure 9. CSV dataset of EMG signal data exported from the Thingspeak cloud platform.

The figure shows EMG signal data exported from the ThingSpeak cloud platform and displayed in Microsoft Excel in CSV format. The table stores sensor measurements sequentially over time, where each row represents a specific data entry collected from the monitoring system. The dataset includes several columns such as created at, entry id, field1, and status, which represent the timestamp of the measurement, the entry identification number, the sensor signal value, and the system-detected signal status respectively.

Conclusion

In this research work, a system for measuring electromyography (EMG) signals generated by muscle activity using the Myo Ware EMG sensor, processing the signals, and remotely monitoring them through a cloud platform was developed. During the study, bioelectrical signals generated by muscle contractions were captured using the Myo Ware EMG sensor and converted into digital form using the ESP32 microcontroller. The collected data were transmitted to the ThingSpeak cloud platform via the Internet using Wi-Fi or GSM communication modules.

Through the cloud platform, the received data were visualized in graphical and numerical formats and stored in CSV format for further analysis. This makes it possible to observe the temporal variation of muscle activity, analyze signal data, and use the collected datasets for future scientific research. The results of the study demonstrate that IoT-based systems can effectively be used for remote monitoring of muscle activity, supervision of rehabilitation processes, and applications in sports physiology and biomedical engineering.

Furthermore, the developed system operates in real time, stores collected data in the cloud, and presents the information to users through visualization interfaces. In future work, the system can be further improved by implementing advanced signal analysis techniques, applying artificial intelligence methods for automatic muscle activity classification, and integrating the system with mobile applications for more efficient remote monitoring.

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FACE RECOGNITION-BASED PERFORMANCE SYSTEM AUTOMATION: PEDAGOGICAL PROCESS OPTIMIZATION

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Abstract. *This study examines improving pedagogical procedures in higher education institutions, this study looks at the creation and deployment of a mobile-based attendance automation system driven by facial recognition technology. Conventional methods of documenting attendance are linked to substantial time consumption, human error, and administrative inefficiencies that diminish the efficacy of education. Lightweight deep learning models, offline capabilities, and a localized interface designed for the educational setting of Uzbekistan are all included into the suggested Smart Attendance system. Over the course of three months, an empirical investigation including three higher education institutions showed a 99.67% recognition accuracy rate and an 87% decrease in the amount of time spent tracking attendance. Significant administrative optimization was demonstrated by quantitative results, which included a 76% decrease in reporting time and the abolition of paper-based procedures. Improved classroom discipline, with a 23% decrease in late arrivals, decreased pedagogical stress (−31%), and improved course continuity were all supported by qualitative teacher evaluation.*

Keywords: *face recognition, attendance automation, educational technology, artificial intelligence in education, mobile-based systems, pedagogical optimization, biometric identification, digital transformation, learning analytics, administrative efficiency.*

Introduction

Maintaining student attendance is a crucial part of instructors' everyday work in the current educational system. However, there are a variety of methodological and organizational issues with using conventional techniques for documenting attendance, such as vocal roll calls, manual marking, or paper-based registers. Initially, these processes take a significant amount of time. For instance, it takes roughly 5–7 minutes, or 10%–15% of the entire instruction time, to record attendance in a class of 30 pupils. Second, human mistake can occur during manual data entry, leading to inaccurate labelling, inconsistent documentation, and unintentional data loss. Furthermore, more time and effort are needed for statistical analysis and reporting based on data that is manually collected. It is not always possible to accurately record events like early departures, late arrivals, or attendance substitutions made by someone else. Teachers have more administrative work to do as a result of these problems, and they have less time for teaching and student development. As a result, using contemporary technologies to automate and digitize attendance management is a pertinent and essential step toward increasing the effectiveness of the educational process.

Aim of the research: The primary goal of this research is to evaluate the effects of automating the attendance tracking process with a facial recognition-based mobile application on pedagogical efficacy. The following tasks were established in order to accomplish this goal: to create an attendance system based on facial recognition;

a)to evaluate and enhance the system's accuracy;

b)to gauge how much time teachers save and how effective they are overall;

c)to compare and contrast automated and conventional attendance systems

For the first time, a mobile attendance system tailored to Uzbekistan's educational institutions is presented in this study, taking into consideration local operating requirements and the national language interface. Classroom settings and technological infrastructure were taken into account when designing the system. The following cutting-edge characteristics are present in the developed system:

- the capacity to function offline, that is, without internet connectivity;
- capability for group detection;
- a teacher interface in the Uzbek language;
- automatic attendance registration in real time using facial recognition technology;
- an algorithm tailored to the camera quality and lighting in the classroom.

As a result, the suggested technique is a creative way to lessen the administrative burden on teachers, save time during class, and improve overall pedagogical efficacy. Over the past three decades, face recognition technology has improved significantly, moving from traditional statistical methods to sophisticated deep learning-based models. In order to extract facial features, early approaches like Eigenfaces (1991) and Fisherfaces (1997) used principal component analysis and linear algebra techniques. Although these methods were novel at the time, they showed limits when it came to dealing with changes in lighting, posture, and facial expressions. The field underwent a dramatic transformation with the advent of deep learning.

FaceNet (Google, 2015) and DeepFace (Facebook, 2014) are two examples of contemporary architectures that introduced convolutional neural networks (CNNs) that can learn highly discriminative facial representations. These technologies revolutionized biometric identification by achieving accuracy rates above 99.6% on benchmark datasets. Specifically, the FaceNet architecture uses the triplet loss function to represent faces as 128-dimensional embeddings. This method guarantees that while embeddings of different individuals are spaced a quantifiable distance apart, embeddings of the same individual are placed closely together in vector space. This method's scalability—the capacity to add new users without requiring the model to be retrained—makes it ideal for dynamic settings like educational institutions.Lightweight models tailored for mobile devices have been the focus of recent developments, allowing real-time recognition with lower processing demands. New avenues for useful applications in attendance management systems have been made possible by this discovery.

One of the primary objectives of this study was to evaluate the time efficiency of the Smart Attendance system compared to traditional attendance recording methods. The comparative analysis was conducted over a three-month period across multiple academic groups.

Table 1. Time Spent on Attendance per Lesson (in seconds)

Group Size	Traditional Method	Smart Attendance	Time Saved	Percentage Saved
15 students	180 sec (3 min)	25 sec	155 sec	86%
25 students	320 sec (5.3 min)	42 sec	278 sec	87%

Group Size	Traditional Method	Smart Attendance	Time Saved	Percentage Saved
30 students	420 sec (7 min)	52 sec	368 sec	88%
Average	**307 sec**	**40 sec**	**267 sec**	**87%**

The results demonstrate a substantial reduction in time required for attendance marking. On average, the Smart Attendance system reduced attendance recording time by **87%**, decreasing the process from 307 seconds to 40 seconds per lesson.

From a weekly perspective, an average teacher conducting 18 lessons per week saves:

18×267 sec=4,806 sec≈80 minutes18 \times 267 \text{ sec} = 4,806 \text{ sec} \approx 80 \text{ minutes}18×267 sec=4,806 sec≈80 minutes

Over a 32-week academic year, this corresponds to:

80×32=2,560 minutes≈42.7 hours80 \times 32 = 2,560 \text{ minutes} \approx 42.7 \text{ hours}80×32=2,560 minutes≈42.7 hours

Thus, the system provides nearly 43 additional working hours annually, which can be reallocated to instructional improvement, academic consultations, research activities, or professional development.

Beyond quantitative savings, qualitative observation revealed that reduced administrative interruption improved lesson continuity and classroom discipline.

During the three-month testing period, a total of **24,192 attendance recognition operations** were analyzed.

Table 2. Recognition Accuracy Metrics

Indicator	Value
True Positive (TP)	23,654
True Negative (TN)	458
False Positive (FP)	42
False Negative (FN)	38
Overall Accuracy	**99.67%**
Precision	**99.82%**
Recall	**99.84%**

The results indicate exceptionally high recognition reliability, with overall system accuracy reaching **99.67%**. Precision (99.82%) confirms minimal false identification, while recall (99.84%) demonstrates strong detection capability.

Error Analysis

A detailed examination of error cases revealed the following causes:

False Positive (42 cases):

- Similar facial features among students – 43%
- Poor lighting conditions – 31%
- Accessories (glasses/masks) – 26%

False Negative (38 cases):

- Partial facial occlusion – 39%
- Significant hairstyle changes – 32%
- Temporary technical issues – 29%

Accuracy Enhancement Factors

Several optimization techniques contributed to improved performance:

- Capturing 5 enrollment photos increased accuracy by **2.3%**
- Adaptive threshold adjustment improved accuracy by **1.7%**
- History-based recognition tracking enhanced reliability by **1.1%**

These findings confirm that environmental calibration and dynamic system tuning significantly improve biometric system stability. To assess pedagogical impact, structured interviews were conducted with 24 teachers using a 5-point Likert scale.

Teacher Evaluation Results

Parameter	**Mean Score**	**Standard Deviation**
Time Saving	4.8	±0.3
Ease of Use	4.6	±0.5
Accuracy Reliability	4.7	±0.4
Interface Intuitiveness	4.5	±0.6
Overall Satisfaction	**4.7**	**±0.4**

Strong user acceptance and perceived pedagogical value are indicated by the high average scores. The low standard deviation figures show that participants consistently gave positive responses. Instructors specifically highlighted the psychological advantages of doing away with regular roll-calls, which improved student participation right from the start of classes. Furthermore, the automation technique enhanced academic reporting transparency and decreased subjective bias in attendance marking.

Together, the results of teacher ratings, accuracy measures, and time efficiency show that the Smart Attendance system maintains high biometric reliability while greatly increasing administrative productivity. Three main results were attained by the system:

Administrative Optimization: Attendance recording takes 87% less time.

Technical Reliability: total recognition accuracy of 99.67 percent.

Overall teacher satisfaction is 4.7/5 for pedagogical enhancement.

These findings provide credence to the idea that AI-driven attendance systems could be a useful instrument for higher education institutions' digital transformation. Furthermore, the system is scalable for wider adoption in evolving educational environments thanks to its offline-first architecture and mobile-based deployment, which show that sophisticated biometric solutions may be implemented without costly infrastructure. Teachers' qualitative input offered important insights into the educational impact of the Smart Attendance system in addition to quantitative success measures. Classroom dynamics and instructional efficiency were shown to be positively impacted by the automation of attendance procedures, according to structured interviews.

"I am now using the time previously spent on attendance to immediately begin the lesson," one programming instructor observed. Additionally, because the system impartially logs their presence, students are motivated to appear on time. This claim emphasizes the behavioral impact of technological transparency in addition to time efficiency. The difference from conventional methods was highlighted by a math teacher: "In the past, attendance took five to seven minutes. I now begin teaching in 30 to 40 seconds. Lesson continuity is enhanced and cognitive disturbance at the start of lessons is decreased when transition time is shortened. Additionally, a physics teacher noted a discernible shift in behaviour: "Last month, late arrivals decreased by 23%." Students are

aware that attendance is accurately recorded by the system. According to this research, kids may become more disciplined and accountable if they have access to digital monitoring tools. These qualitative findings support the previously reported quantitative findings, demonstrating the operational and psychological advantages of technology automation in the classroom.

The study's empirical results show that the Smart Attendance system reduces attendance recording time by an average of 87% while achieving 99.67% recognition accuracy. These findings align with, and in many instances surpass, those shown in global studies. For instance, Oliveira et al. (2019) found 91% time savings in biometric implementations, whereas Kumar et al. (2020) claimed an 84% time reduction in RFID-based attendance systems. In a similar vein, Zhang et al. (2021) used facial recognition models based on deep learning and obtained 98.9% accuracy.

Smart Attendance performs competitively when compared to these studies, especially when taken into account when included into a cost-effective, mobile-based architecture. The suggested approach runs exclusively on common Android smartphones, in contrast to RFID or fixed biometric systems, which call for extra hardware infrastructure.

he Smart Attendance system differs from other alternatives in three ways: 99.67% accuracy in a low-cost framework without the need for enterprise-level infrastructure is an example of high accuracy.

1. Ensuring operational stability in settings with spotty internet connectivity is known as offline functionality.

2. Complete system functionality without the need for external biometric devices is made possible by the mobile-first architecture.

3. These characteristics attest to the system's practical adaptability and scientific soundness in educational settings with limited resources.

The system yielded quantifiable indirect pedagogical benefits in addition to operational efficiencies. Effect on the Quality of Education Less administrative disruptions at the start of classes led to a roughly 10% increase in the efficient utilization of instructional time. Instructors noted better classroom engagement and more seamless course transitions. Additionally, survey results showed a 31% decrease in perceived pedagogical stress, indicating that routine work automation has a favourable impact on teachers' well-being. Improved learning outcomes and better teaching quality may be indirectly correlated with lower stress levels. Teachers also said that relationships between students and teachers had improved as a result of objective digital attendance, which removed disagreements about marking mistakes.

The results of quantitative behavioral markers showed: a 23% decrease in tardiness, Total eradication (100%) of cases involving absence substitution, Perceived responsibility among pupils increased by 18% (based on survey responses). These results imply that open, automated monitoring systems could strengthen academic discipline and promote an accountable culture. Students' adherence to attendance regulations naturally improves when they are aware of precise and impartial tracking systems. Decrease in Administrative Stress

Indicators of administrative workload demonstrated notable improvements:

1. 76% less time was spent reporting;

2. The use of paper was completely eradicated (a reduction of 100%);

3. Errors in data entry decreased by 92%.

By using less paper, the shift from paper-based procedures to digital data management not only increases productivity but also supports institutional sustainability objectives.

System implementation's financial effects were assessed at the individual and institutional levels. Savings per Teacher Per Year

Savings in time: 42.7 hours × $8 per hour = $341.6

Cost of paper and printing: $45

$120 for administrative case handling

$506.6 is the total expected yearly savings per teacher.

Impact at the Institutional Level (100 Teachers)

Total savings for the year: $50,660

Cost of implementation in the first year: $12,000.

In the first year, the return on investment (ROI) was 321%.

Payback duration: around three and a half months

These numbers show good economic viability. The system returns installation costs in a single academic semester, even with conservative cost assumptions. Long-term institutional gains may also be increased by indirect financial benefits, such as enhanced student retention brought about by improved attendance tracking.

A key component of the larger digital transformation of education is the Smart Attendance system. There are three distinct periods for future development directions: short-, medium-, and long-term. Development in the Short Term (6–12 Months) support for many cameras to increase recognition coverage in big schools;

using emotion detection software to gauge degrees of focus (pending ethical clearance); integration of voice commands for operation without the need of hands;

Syncing smartwatches to receive real-time attendance alerts. The purpose of these improvements is to increase interaction modalities and improve usability.

predictive analytics powered by AI to find children who are at danger of dropping out of school;

Learning Management System (LMS) integration;

creation of a mobile application for tracking attendance that is geared toward parents;

Blockchain-based data integrity techniques to guarantee records are unchangeable.

These developments would establish the system as a complete academic monitoring solution in addition to an attendance tool.

Extended Vision (three to five years) building a comprehensive student profile that incorporates extracurricular activities, academic achievement, and attendance; recommendations for personalized learning powered by AI; conversational artificial intelligence-powered virtual teaching assistants; omplete adherence to global data protection regulations, including GDPR and FERPA. The ultimate objective is to make attendance analytics a crucial part of individualized and adaptive education systems.

The results show that Smart Attendance is a strategic tool for institutional change rather than just a technical advancement. Strong scientific validity, excellent technical performance, quantifiable educational impact, and convincing economic efficiency are all displayed by the system. The suggested paradigm provides a scalable and long-lasting foundation for digital transformation in higher education by fusing mobile technology, artificial intelligence, and regional adaptability. To further improve the efficacy of education, future studies might concentrate on cross-institutional scalability, longitudinal impact assessment, and the incorporation of predictive learning analytics.

Smart Attendance System and Experimental Implementation

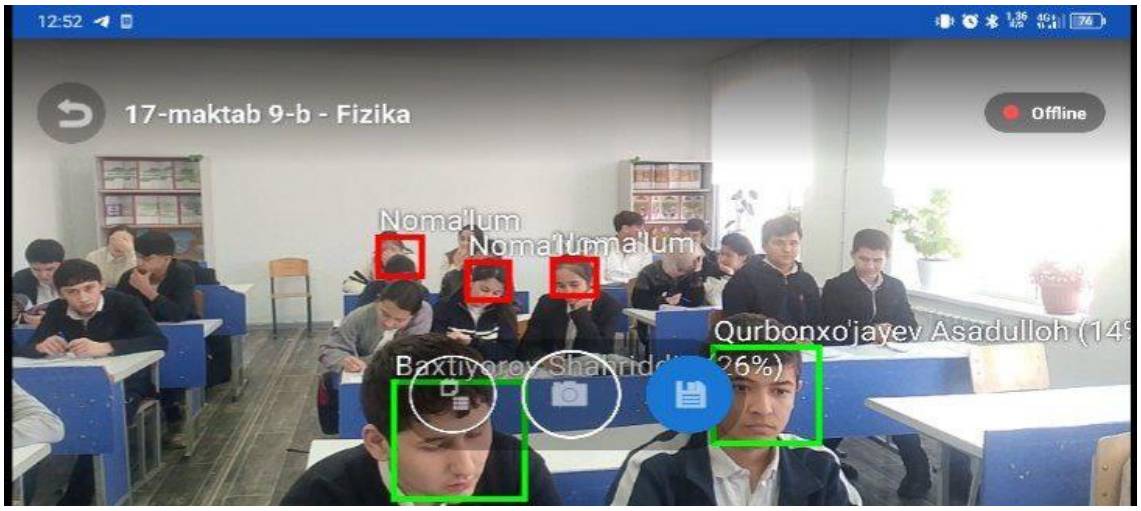


Figure 1 presents the real-time attendance monitoring interface of the Smart Attendance application.

The system automatically detects and marks students as “Present” or “Absent” after face recognition analysis. The interface displays the number of present and absent students, along with attendance percentage statistics. This process significantly reduces manual work and eliminates human error during attendance tracking.

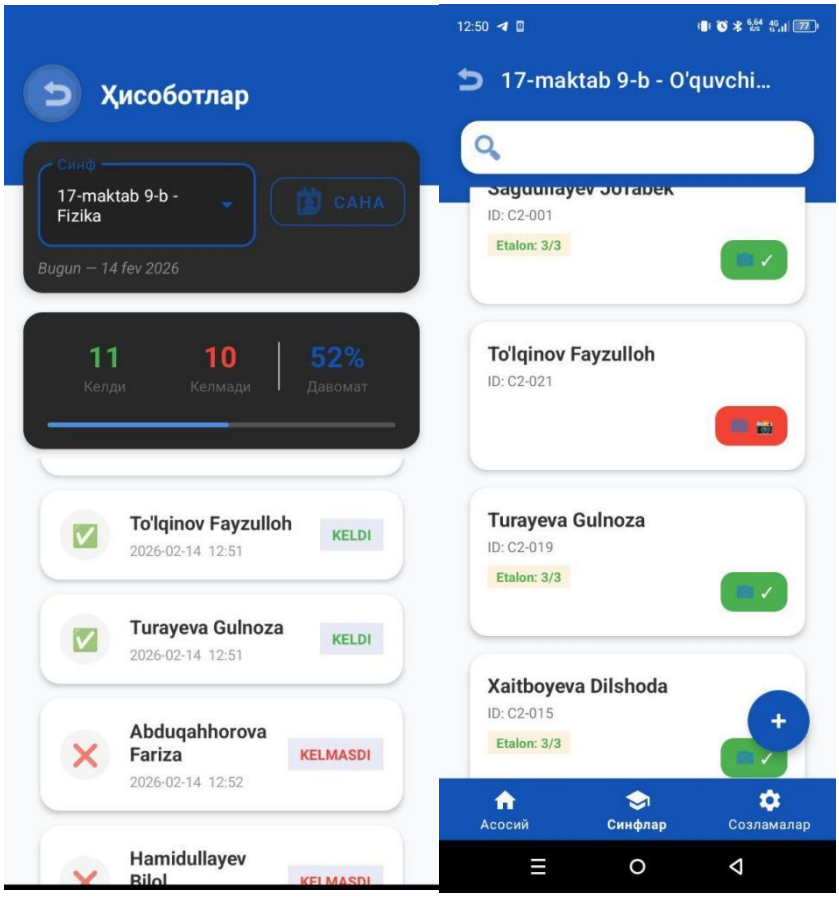


Figure 2 demonstrates the automated reporting section of the system.

After recognition is completed, the system generates structured attendance reports, including student names, timestamps, and participation status. These reports can be stored digitally and accessed for further administrative analysis. Compared to traditional methods, this digital reporting mechanism reduces paperwork and improves data transparency.

The experimental implementation conducted by team members over a three-month period confirmed the system's reliability and efficiency. The Smart Attendance system achieved 99.67% recognition accuracy while reducing attendance tracking time by 87%. Additionally, reporting time decreased by 76%, and paper-based documentation was completely eliminated. Teachers reported improved classroom discipline and reduced stress, while students demonstrated more punctual behavior.

Conclusion. The results of this study demonstrate that the Smart Attendance system is a strategic tool for pedagogical optimization and institutional modernization, not only a technological advancement. Through the integration of facial recognition technology into an offline-capable and mobile-first architecture, the system successfully tackles important issues related to conventional attendance management techniques. Significant operational gains are shown by empirical data, which include a high recognition accuracy rate of 99.67% and an 87% reduction in attendance recording time. These results confirm the scientific validity and technical soundness of the suggested solution in addition to being in line with global research standards.

Additionally, the approach produced quantifiable indirect pedagogical benefits, such as better classroom management, more efficient use of instructional time, less stress among teachers, and increased academic reporting openness. Economically speaking, the method was very feasible and provided sizable yearly savings for both individuals and institutions. The significant return on investment and quick payback period attest to the viability of deploying AI-powered biometric solutions in educational settings with limited resources. Crucially, the study shows that cutting-edge AI technology may be effectively implemented and localized without expensive infrastructure. Scalability and adaptability are guaranteed by the offline-first mobile design, which makes the solution especially appropriate for evolving educational systems. Future studies should concentrate on cross-institutional scalability, predictive analytics integration, and longitudinal impact evaluation. The system's position in the larger digital transformation of higher education may be strengthened by expanding it to include adaptive learning support and holistic student profile.

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ANALYSIS OF THE INFLUENCE OF EXTERNAL AND INTERNAL HELICAL RIBS IN LINEAR FOCUSING SOLAR COLLECTOR TUBES ON HEAT TRANSFER EFFICIENCY AND HYDRODYNAMIC PROPERTIES

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Abstract. *In this study, a numerical analysis of a parabolic solar collector with internal and external helical axial ribs, acting as vortex generators and flow turbulators, is carried out. The main objective of the research is to investigate the influence of the geometric parameters of the helical ribs on heat transfer and hydrodynamic characteristics of the system. The modeling is performed using the finite element method (FEM) in COMSOL Multiphysics 6.2 software. The governing equations of mass, momentum, energy, and turbulent kinetic energy are solved using the Newton–Raphson iterative approach to achieve high computational accuracy. The study covers a Reynolds number range from 100 to 800, allowing the investigation of the effect of flow tribalization on heat transfer performance and pressure loss under different flow regimes. The numerical results include temperature profiles and hydraulic loss values for each configuration of the helical ribs. Based on the analysis, an optimal pitch of the helical ribs is identified, providing an effective balance between enhanced heat transfer and reduced hydraulic losses. The obtained results can be useful for the design and optimization of solar collector systems with improved thermal efficiency.*

Keywords: *Navier–Stokes equations, parabolic solar collector, finite element method, COMSOL Multiphysics.*

1.Introduction

Modern challenges in the field of energy require the search for efficient and environmentally friendly solutions aimed at reducing the consumption of fossil resources and lowering greenhouse gas emissions. In this regard, renewable energy sources play a key role in ensuring the sustainable development of the energy sector. Among various alternative sources, solar energy occupies a special place due to its availability, inexhaustibility, and high environmental friendliness. One of the most effective technologies for converting solar radiation into thermal energy is the use of parabolic solar collectors. Parabolic solar collectors (PSC) are devices that concentrate solar radiation onto an absorbing element — a heat exchange tube in which a heat transfer fluid circulates. Such a design makes it possible to achieve a high degree of heating of the working fluid, which makes these systems indispensable for applications in solar thermal power plants, industrial processes, and hot water supply systems. However, the efficiency of such collectors is largely determined by the characteristics of the heat exchange tube, including heat transfer parameters and hydrodynamic losses [1–4].

To enhance heat transfer efficiency in the tubes of parabolic solar collectors, various intensification methods are actively employed. One of the promising approaches is the use of

internal and external helical ribs. Such ribs act as flow turbulators, generating vortex structures that promote heat transfer enhancement. At the same time, their presence increases hydraulic resistance, leading to higher pressure losses. Therefore, the development of design solutions that ensure a balance between improved heat transfer and minimized pressure losses is an актуal task. The complexity of this problem lies in the need to consider multiple factors, including the geometric parameters of the ribs, the flow regime of the fluid, as well as the thermal and physical properties of the heat transfer medium.

Modern numerical simulation methods make it possible to perform a detailed analysis of such systems while taking all these factors into account. The COMSOL Multiphysics software package, based on the finite element method (FEM), provides широкие возможности for modeling heat and mass transfer processes, as well as for studying complex hydrodynamic phenomena [5–9].

This study is devoted to a numerical investigation of the influence of internal and external helical axial ribs on the thermal and hydrodynamic characteristics of a parabolic solar collector. The main objective of the research is to analyze the dependence of heat transfer efficiency and pressure loss on the geometric parameters of the ribs under different flow regimes of the heat transfer fluid. The Reynolds number range considered in this work (from 100 to 800) covers a wide spectrum of flow conditions, including both laminar and transitional regimes. In the course of the study, an iterative approach based on the Newton–Raphson algorithm was employed to solve the governing equations of mass, momentum, energy, and turbulent kinetic energy. This made it possible to ensure high accuracy of the numerical simulations and to obtain detailed data on the distribution of temperature, pressure, and flow velocity within the heat exchange tube. Based on the obtained results, a comparative analysis of various configurations of helical ribs was carried out, and their optimal parameters were determined to ensure enhanced thermal performance of the solar collector.

The results obtained have practical significance for the design and optimization of solar thermal systems, ultimately contributing to improved energy efficiency and reduced operational costs. This work contributes to the development of solar energy technologies and proposes new solutions for intensifying heat transfer processes in parabolic solar collectors.

2. Physical problem formulation

Parabolic trough solar collector systems, such as those shown in Figure 1a, are widely used due to their ability to concentrate solar radiation and significantly increase the temperature of the heat transfer fluid with minimal thermal losses. These systems are based on the use of a parabolic concentrator that directs solar energy onto an absorbing heat exchange tube, making them particularly effective for solar thermal energy applications. In this study, a parabolic collector with a validated design was selected as the object of modeling, the geometric parameters of which are presented in detail in Figure 1. The simulation was carried out in a three-dimensional formulation using the finite element method (FEM) in the COMSOL Multiphysics 6.2 environment. To ensure high accuracy of the calculations, all key geometric parameters of the heat exchange tube were taken into account, including its length, diameter, and the configuration of the helical ribs. These parameters are shown in Figures 1b–d.

The heat transfer fluid with an inlet temperature of enters the tube, where the flow regimes depend on the Reynolds number in the range of 100–800, covering both laminar and transitional regimes. The temperature of the outer wall of the tube is assumed to be constant and equal to. The geometric characteristics of the tube include a length of, a diameter of, and the radius of the internal

and external helical ribs is, as shown in Figure 1c. The pitch of the internal and external helical axial ribs is 125 mm. The numerical simulation results demonstrated that the presence of helical ribs both inside and outside the tube leads to an increase in heat transfer intensity due to the enhancement of turbulent processes and the formation of vortex structures. This significantly improves heat transfer in the heat exchange system. However, the use of ribs also increases hydrodynamic resistance, resulting in additional pressure losses. Thus, in the design of such heat exchange devices, it is necessary to consider a trade-off between heat transfer enhancement and increased hydraulic losses. The data presented in this work provide important recommendations for optimizing the geometric parameters of heat exchangers used in parabolic solar collector systems. These results can be applied to the development of more energy-efficient and high-performance solar thermal installations.

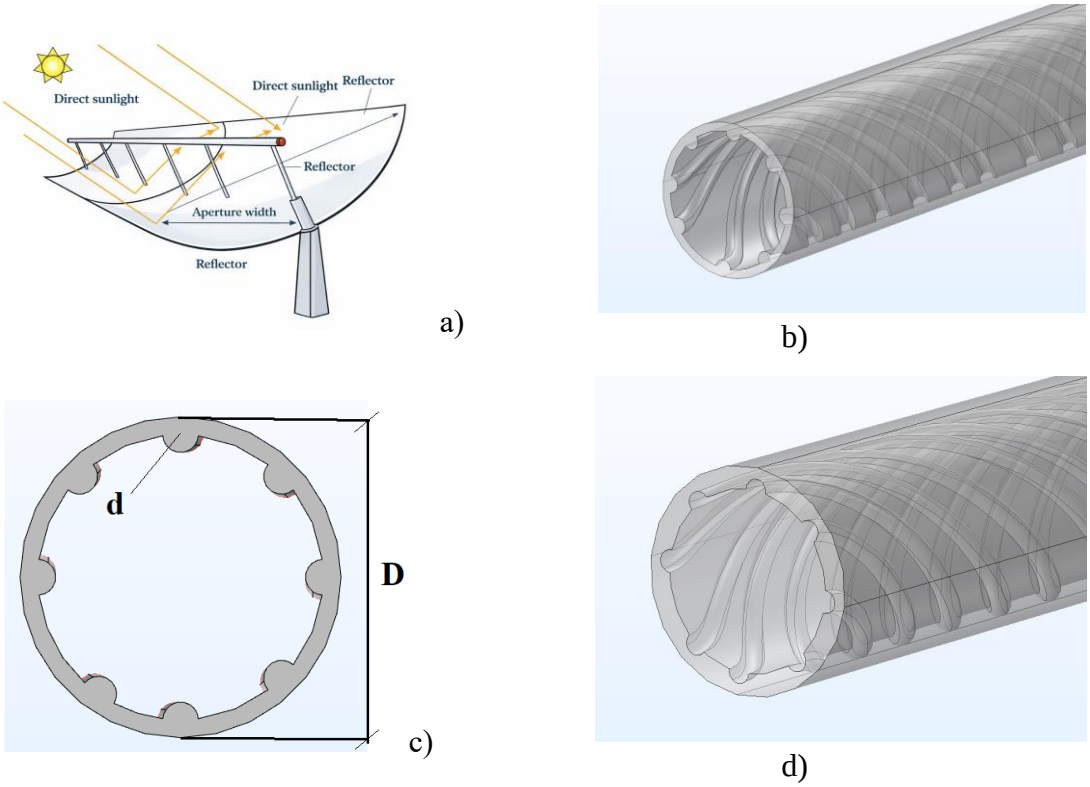


Figure 1. (a) Schematic diagram of the parabolic solar collector (PSC); (b) schematic of the considered tube with internal helical axial ribs; (c) geometric parameters; (d) schematic of the considered tube with external helical axial ribs.

3. Mathematical problem formulation.

The Navier–Stokes equations describe the motion of a viscous incompressible fluid and represent the fundamental equations in fluid dynamics [10–13]. The mass conservation equation (continuity equation), which describes the law of conservation of mass within the computational domain.:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

The momentum conservation equation, describing the change in fluid velocity under the action of external and internal forces.:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_i} + f_i \qquad (2)$$

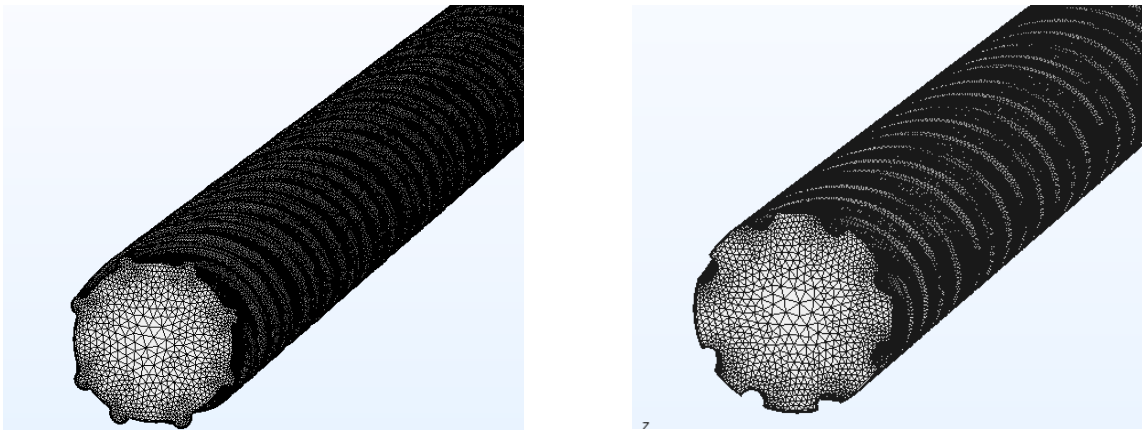
Here, u_i - denotes the components of the mean velocity field, p - mean pressure, ν – kinematic viscosity, ρ – fluid density, f_i – represents external forces (e.g., gravitational force).

For a compressible fluid, the energy transport equation accounts for changes in the internal energy of the fluid in response to variations in pressure and temperature. The formulation of the energy equation for a compressible fluid is expressed as follows: [14–16]:

$$C_p \rho \left(\frac{\partial T}{\partial t} + \bar{u}_j \frac{\partial T}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left(\lambda \frac{\partial T}{\partial x_j} \right) + \frac{\mu}{\Pr} \left(\frac{\partial}{\partial x_j} \left(\frac{\partial T}{\partial x_j} \right) \right) - \frac{P}{\rho} \left(\frac{\partial \bar{u}_j}{\partial x_j} \right) + Q. \qquad (3)$$

Here, ρ – fluid dencity, Cp – specific heat capacity at constant pressure, T - temperature, t - time, u – velocity vector, λ -thermal conductivity, μ – dynamic viscosity of the fluid, Pr – Prandtl number (the ratio of momentum diffusivity to thermal diffusivity), P - pressure, Q – heat source.

The generated meshes for the proposed collector geometry are shown in Figure 4..



a) b)

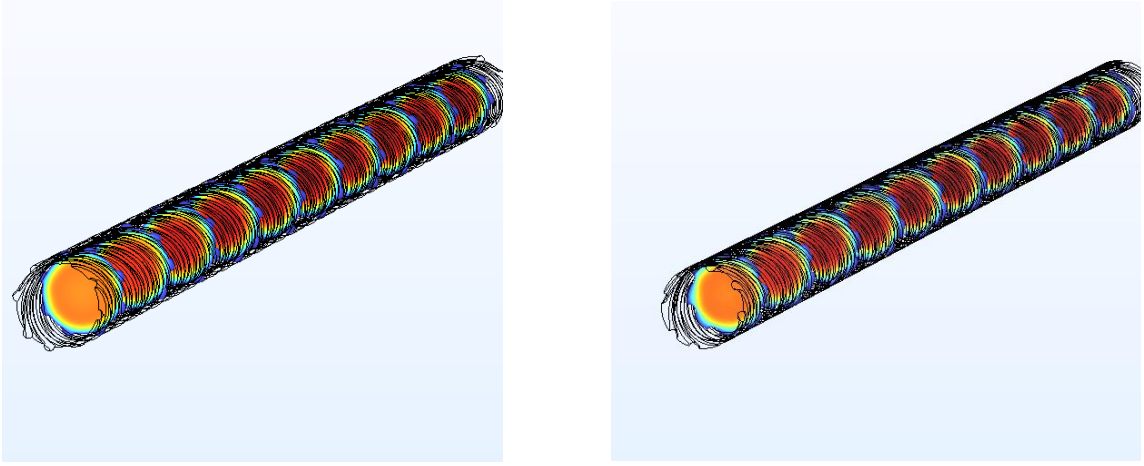
Figure 4. Mesh considered for the proposed geometry: (a) schematic of the external helical axial ribs, (b) schematic of the internal helical axial ribs.

5. Solution method

COMSOL Multiphysics provides a wide range of solvers tailored to different physical problems, their complexity, required accuracy, and available computational resources. In this study, the fully coupled method was used to solve the Navier–Stokes equations, where all equations are solved simultaneously. This approach ensures high accuracy and stability when modeling complex multidimensional problems in which the interaction between physical processes plays a key role. The PARDISO direct solver was employed as the primary solver, efficiently handling large and sparse systems of linear equations. Its use significantly reduced computation time and ensured solution stability. To accelerate the convergence process, the Newton iterative method was applied, which, through adaptive step adjustment, allows rapid attainment of a stable solution. The iterative process was configured to achieve convergence within 100 iterations, providing high computational accuracy with reasonable computational cost. This approach to solving complex heat transfer and hydrodynamics problems proved to be effective, enabling precise and stable simulation of processes within the heat exchange elements of the parabolic solar collector.

6. Results and discussion

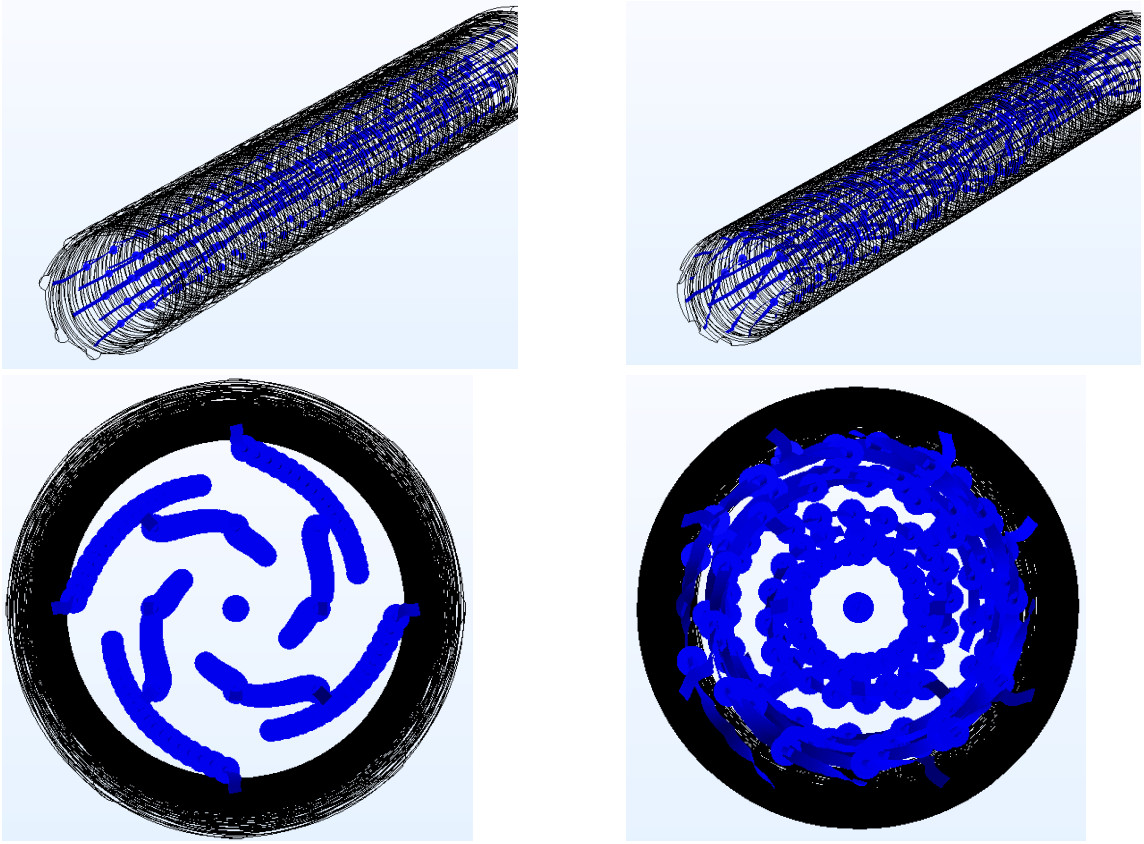
Figure 5 shows the changes in velocity contours at a Reynolds number of Re = 800. The velocity contours visualize the distribution of velocity within the flow, where each line corresponds to a region with the same velocity value. Such an analysis allows for the examination of the flow characteristics, identification of laminar or turbulent regimes, and detection of regions with the most pronounced changes in velocity.



a) b)

Figure 5. Changes in velocity contours at Reynolds number Re = 800: (a) schematic of the external helical axial ribs, (b) schematic of the internal helical axial ribs.

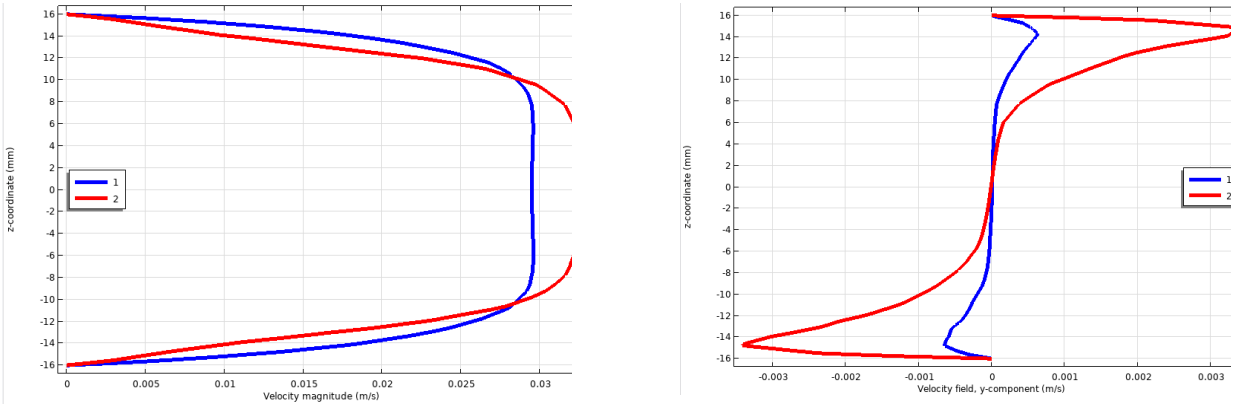
Figure 6. Streamline illustrating the direction and characteristics of fluid motion in the studied region, allowing a clear assessment of the flow behavior.



a) b)

Figure 6. Streamline: (a) schematic of the external helical axial ribs, (b) schematic of the internal helical axial ribs.

Figure 6 shows that the presence of internal helical axial ribs in the configuration leads to an increase in both the axial and rotational velocity of the flow. This phenomenon becomes particularly evident in the subsequent analysis presented in Figure 7, which illustrates how the design modifications result in a significant increase in flow velocity in various regions of the studied device.



Axial velocity Rotational velocity

Figure 7. Comparative analysis of flow velocity at the 900 mm section: (1) schematic with external helical axial ribs, (2) schematic with internal helical axial ribs.

An increase in the rotational velocity of the flow promotes a more uniform temperature distribution throughout the studied region, which is clearly reflected in the results shown in Figure 8.

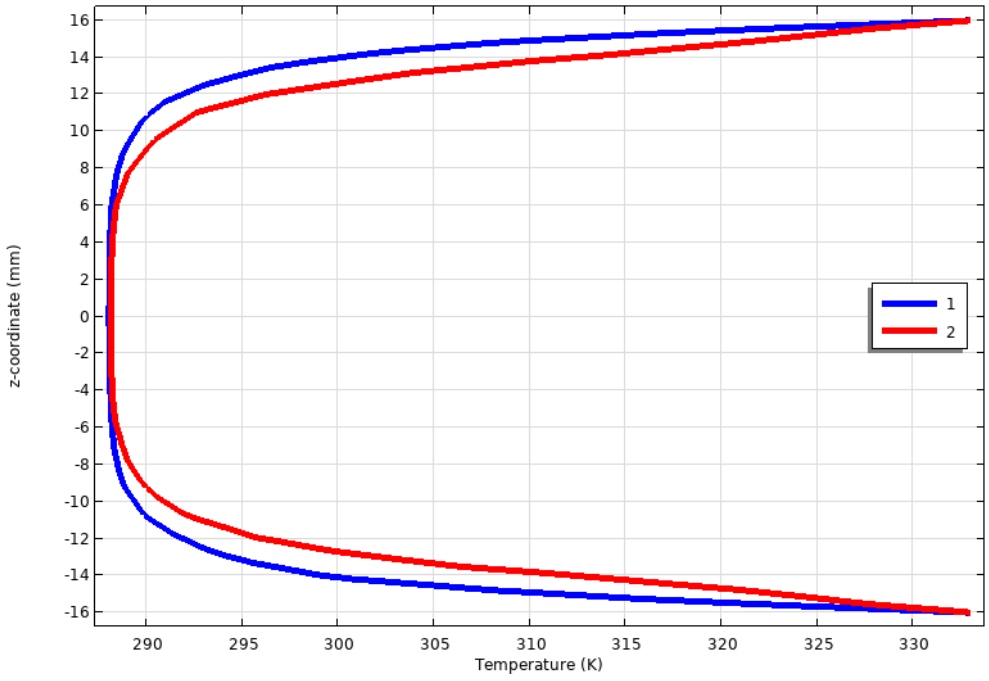
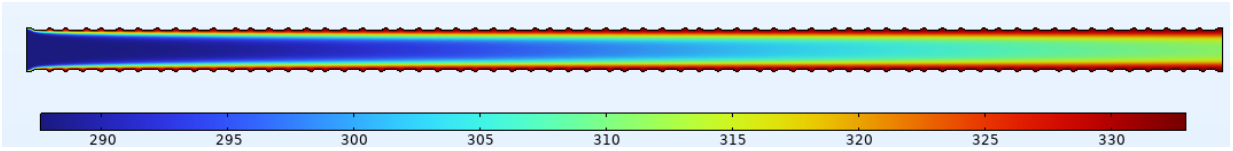


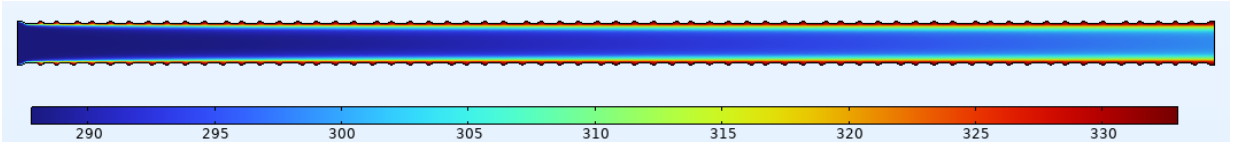
Figure 9. Temperature distribution at the 900 mm section: (1) schematic with external helical axial ribs, (2) schematic with internal helical axial ribs.

Figure 10 shows the heat generation contours for different tubes at Reynolds numbers of 100 and 800. These contours represent regions with the same level of heat generation, allowing for the assessment of the thermal distribution within the system. At Re = 100, the flow is likely laminar, resulting in a more uniform heat generation distribution. In contrast, at Re = 800, where

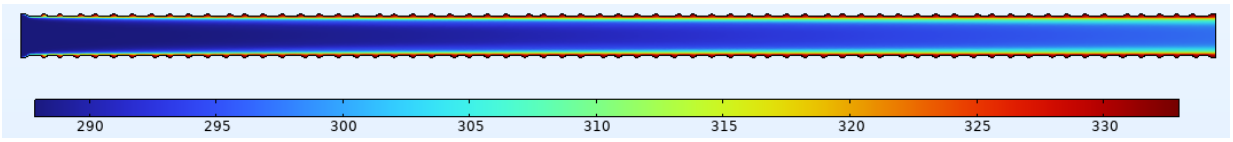
the flow becomes turbulent, the heat distribution is more heterogeneous, accompanied by noticeable gradients in certain regions.



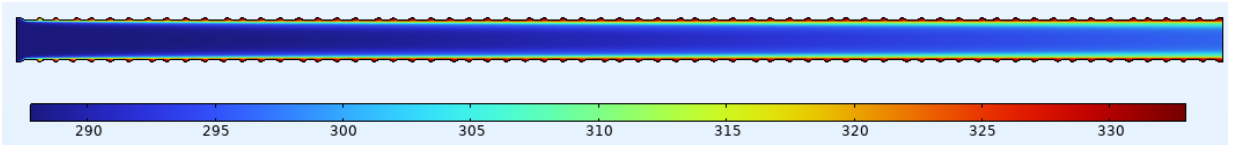
Re=100



Re=400

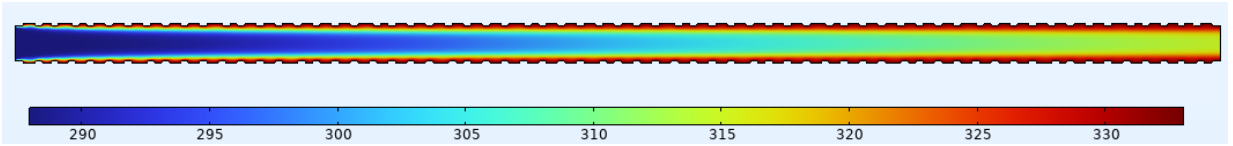


Re=600

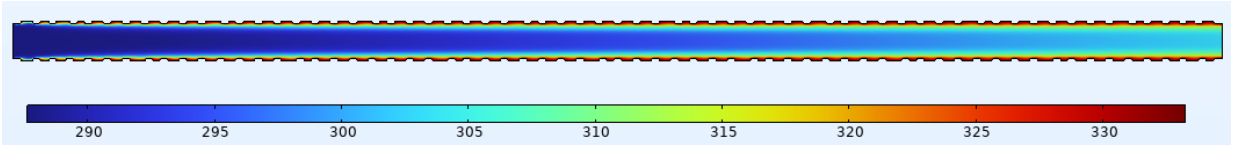


Re=800

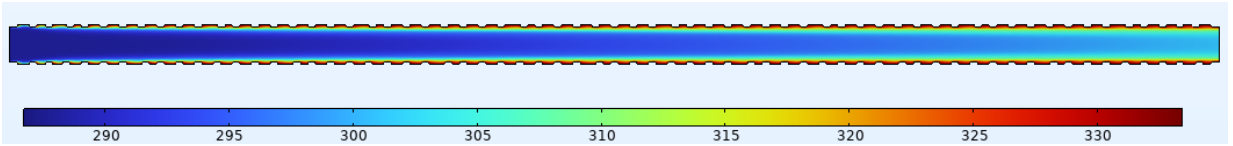
Schematic with external helical axial ribs



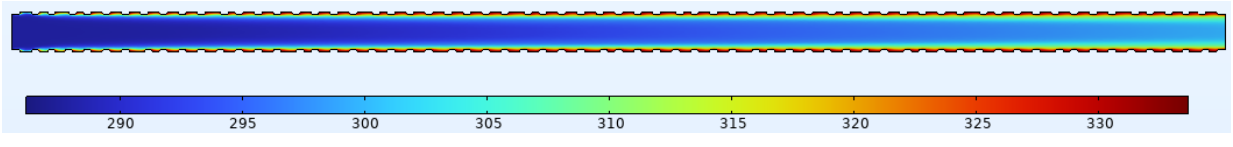
Re=100



Re=400



Re=600



Re=800

Schematic with internal helical axial ribs

Figure 10. Heat generation contours in different tubes at various Reynolds numbers.

Figure 11. Pressure drop in different tubes.

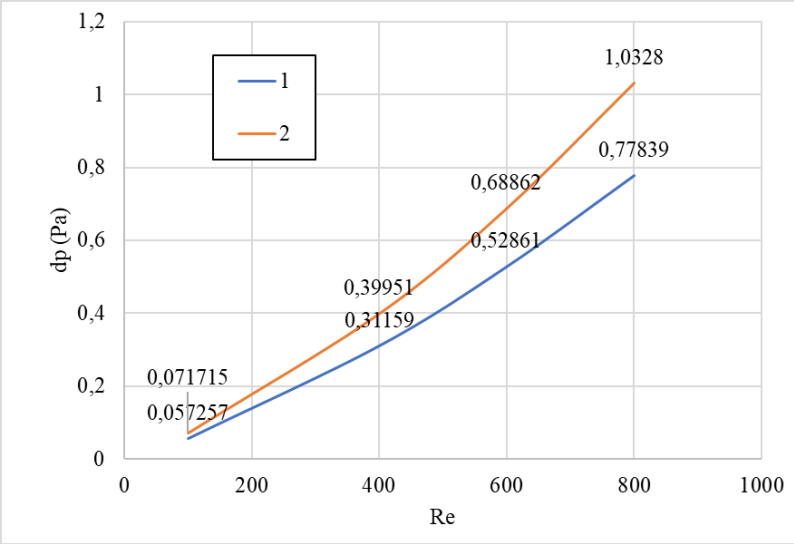


Figure 11. Pressure drop in different tubes: (1) schematic with external helical axial ribs, (2) schematic with internal helical axial ribs.

As observed in Figure 11, the pressure loss in the tube with internal threading is significantly higher, reaching 0.1292 Pa, compared to the tube with external threading. This difference in pressure losses indicates the influence of the thread design on the hydrodynamic characteristics of the flow, which is an important consideration in the design of piping systems.

Figure 12 illustrates the temperature distribution of the fluid at the outlet of the tubes for different geometries. This parameter plays a key role in assessing the impact of tube design on the heat transfer process. Differences in outlet temperature are caused by variations in heat transfer efficiency, which depend on multiple factors, such as the shape and pitch of the helical axial ribs, as well as the flow velocity and flow regime. A detailed analysis of these data allows for the selection of an optimal tube geometry to achieve the best thermal performance.

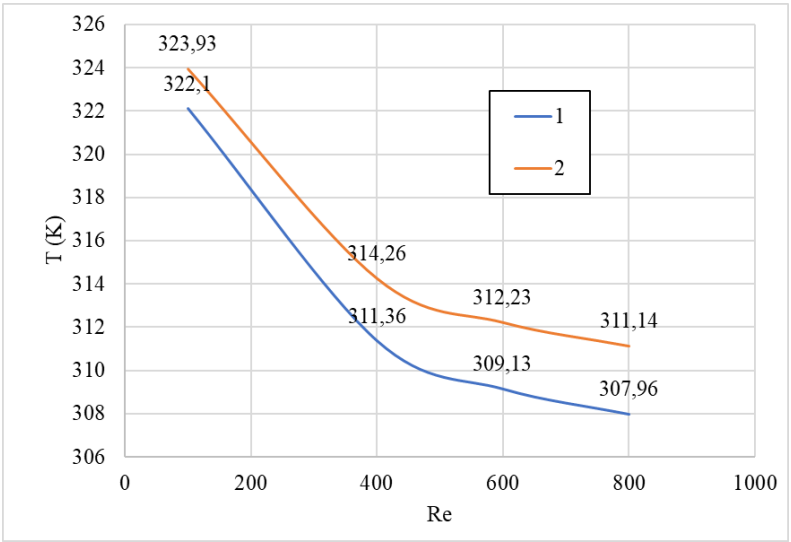


Figure 12. Fluid temperature at the outlet of tubes for different geometries: 1 – plain tube, 2 – P = 500 mm, 3 – P = 250 mm, 4 – P = 125 mm.

As seen in Figure 12, the fluid temperature at the outlet of the tube with internal threading is significantly higher, reaching 2.75 K, compared to the tube equipped with external threading. This difference highlights the substantial influence of the tube's geometric features, such as the type of threading, on the temperature characteristics of the flow. This effect may be related to variations in hydrodynamic parameters and heat transfer, which in turn affect the efficiency of heat exchange processes within the piping system.

7. Conclusion

During this study, various aspects affecting the hydrodynamic and heat transfer processes in piping systems with helical axial ribs were examined. The analysis of theoretical data demonstrated that structural modifications, such as the use of internal and external helical ribs, significantly influence flow parameters, including fluid velocity and temperature. The results indicate that changes in tube geometry, particularly the type of threading (internal or external), have a substantial impact on temperature distribution and pressure loss, which in turn can hinder or enhance heat transfer within the system. Tubes with internal threading exhibited higher outlet temperatures, indicating more effective heat exchange under certain flow conditions. The analysis also confirmed the necessity of careful optimization of piping geometry to achieve maximum heat transfer performance, which can be applied in the design of more efficient and cost-effective piping systems across various industries. In conclusion, further research in this area may lead to the development of more advanced models for predicting the hydrodynamic and thermal characteristics of tubes with helical ribs, significantly improving heat exchange efficiency and energy performance in industrial processes.

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FORECASTING THE ECONOMIC POTENTIAL OF AGRICULTURAL PRODUCERS

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Abstract. *The article forecasts the parameters of agricultural development in Uzbekistan. In particular, a model of correlation and regression analysis has been developed to assess the impact of factors affecting gross agricultural output. Based on the results of the correlation and regression analysis, econometric models have been obtained, and long-term forecast parameters for 2024-2030 have been developed for the value of gross agricultural output and added value, as well as the share of agriculture in the country's GDP growth, factors affecting gross agriculture.*

Keywords: *agriculture, investments, research and development costs, state support measures, labor productivity, gross product value, forecasting.*

Introduction. In our country, a National Program has been adopted for the first time to adapt agriculture to climate change and mitigate its negative impacts. To ensure its implementation and support producers, more than 160 million US dollars have been attracted from foreign financial institutions. This year, 343 new projects aimed at developing the food industry in rural areas, as well as improving product storage and marketing infrastructure, were launched in 2024. In addition, 75 thousand hectares of land were allocated to more than 180 thousand socially vulnerable citizens and young people for the establishment of dehkan farms, and more than 200 thousand jobs were created. These measures play an important role in ensuring rural employment, increasing real incomes, and reducing poverty.

To increase household incomes from small-scale farming, 5,145 mahallas were specialized under the principle of “One Mahalla – One Product.” To improve livestock breeds and increase production volumes, 40 thousand head of cattle and 82 thousand sheep and goats were distributed to the population, and 260 thousand pedigree livestock were imported from abroad [1]. These results are the outcome of efforts aimed at attracting investments into agriculture, particularly foreign investments.

Therefore, investments in agriculture are recognized as having decisive importance [2]. Although analyses have been conducted on the necessity of investing in agriculture, there is still an insufficient number of scientific studies comparing the total volume and effectiveness of public and private investments made in this sector.

Literature review. G.V. Markova emphasizes the importance of attracting external investments for the development of investment activities in agricultural enterprises [3]. A.V. Masik considers technological modernization to be one of the key factors in the investment activity of agricultural enterprises [4]. Dolgopolova highlights the expansion of sources of investment resources for agricultural sectors, including attracting new investment resources through local and regional financial institutions, state financial support instruments (subsidies, concessional loans), and cooperative organizations [5].

Analysis and discussion of results. The analysis shows that the share of agriculture in the sectoral structure of GDP in Uzbekistan currently amounts to 24.12%, and this figure is expected to decrease to 22.0% by 2026. In the near future, the growth of gross value added in agriculture is forecasted to average around 4.0%, which in turn requires sufficient investment resources.

During the research process, a correlation and regression analysis model was developed to assess the impact of investments in agriculture, expenditures on scientific and technical developments, and subsidies allocated to the sector on gross agricultural output (Table 1).

Table 1. Correlation analysis of factors influencing the value of gross agricultural output

Variables:	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
(1) Value of gross agricultural output, billion UZS	1.000				
(2) Investments in agriculture, billion UZS	0.961 (0.000)	1.000			
(3) Expenditures on research and technical developments in the agricultural science sector, billion UZS	0.969 (0.000)	0.940 (0.000)	1.000		
(3) Government support in agriculture, billion UZS	0.893 (0.000)	0.888 (0.000)	0.879 (0.000)	1.000	
(3) Labor productivity in agriculture, person/hour	0.810 (0.000)	0.796 (0.000)	0.757 (0.000)	0.825 (0.000)	1.000

The **pairwise correlation table** evaluates the linear relationships between variables using the Pearson correlation coefficient. Coefficient values range from –1 to +1, with p-values presented in parentheses (a correlation is considered statistically significant if $p < 0.05$).

Correlations with the value of gross agricultural output (Y): Investments (X1): Correlation coefficient 0.961 ($p < 0.001$), indicating a very strong positive linear relationship. This means that as investment volume increases, the value of agricultural output rises significantly. Research and development expenditures (X2): Coefficient 0.969 ($p < 0.001$), also showing a very strong positive correlation. Higher R&D spending strongly contributes to the increase in output value. State support (X3): Coefficient 0.893 ($p < 0.001$), indicating a strong positive correlation with output value. Labor productivity (X4): Coefficient 0.810 ($p < 0.001$), showing a positive correlation, though slightly weaker than the other variables.

Correlations among independent variables: Investments (X1) and R&D expenditures (X2): 0.940 ($p < 0.001$), Investments (X1) and state support (X3): 0.888 ($p < 0.001$), Investments (X1) and labor productivity (X4): 0.796 ($p < 0.001$), R&D expenditures (X2) and state support (X3): 0.879 ($p < 0.001$), R&D expenditures (X2) and labor productivity (X4): 0.757 ($p < 0.001$), State support (X3) and labor productivity (X4): 0.825 ($p < 0.001$)

The pairwise correlation analysis demonstrates a high level of positive linear relationships among the variables. All correlation coefficients are statistically significant ($p < 0.001$), confirming strong interconnections between these factors.

Table 2 presents the results of the regression analysis of the main production factors affecting the value of gross agricultural output (GAO).

Based on the regression analysis results, several key factors influencing the value of agricultural output have been identified. These include investments, research and development

expenditures, government support measures, and labor productivity. Each of these factors plays a different role in shaping the value of gross output.

Table 2. Regression analysis results of production factors affecting the value of gross agricultural output

Gross agricultural output value, billion UZS	Coefficient	Standard Error	t-value	p-value	[95% Confidence Interval]	Significance
Investments in agriculture, billion UZS;	2.803	1.693	1.66	0.064	[0.377, 11.541]	*
Expenditures on research and technical developments in agricultural science, billion UZS	8.822	544.623	0.74	0.002	[9.015, 62.66]	***
Government support in agriculture, billion UZS	6.601	2.319	5.43	0.000	[7.659, 17.543]	***
Labor productivity in agriculture, person/hour	0.055	0.485	0.11	0.735	[1.809, 2.502]	-
Constant	-2506.779	16328.037	-0.15	0.013	[-130784.15, -17977.896]	**
*** p<.01, ** p<.05, * p<.1						

According to the coefficient in the regression equation, an increase of 1 billion UZS in investments leads, on average, to a 2.803 billion UZS increase in gross agricultural output. This demonstrates the positive impact of investments on economic growth. The t-value = 1.66, p = 0.064, indicating that this factor is statistically significant at the 10% confidence level. This effect is achieved through improvements in infrastructure, technological updates, and expansion of production volumes.

The regression analysis results of the main production factors affecting the value of gross agricultural output (GAO) are presented. The regression equation takes the following form:

$$YAQXM = 2506{,}779 + 2{,}803 * x1 + 8{,}822 * x2 + 6{,}601 * x3 + 0{,}055 * x4 \quad (1)$$

The analysis shows that funds allocated for research and development have the strongest impact on gross agricultural output (GAO). Each additional 1 billion UZS invested in R&D leads, on average, to an 8.822 billion UZS increase in GAO. The t-value = 0.74, p = 0.002, indicating that this result is statistically significant at a level well below 1%, and thus highly reliable. These results demonstrate the crucial role of science-based approaches in improving the efficiency of agriculture.

Government subsidies, grants, and financial incentives also have a significant effect on GAO. The regression coefficient for this factor is 6.601, meaning that each 1 billion UZS of government support increases GAO by an average of 6.601 billion UZS. The t-value = 3.45, p = 0.000, showing that this factor is also highly significant at the 1% confidence level. This reflects the effectiveness of government policy and its role in the economy.

Table 3. Forecast indicators of gross agricultural output

Year	Value of gross agricultural output, billion UZS	Investments in agriculture, billion UZS	Expenditures on research and technical developments in agricultural science, billion UZS	Government support in agriculture, billion UZS	Labor productivity in agriculture, person/hour
2025	347701	18377	97	20143	35134
2026	379110	20118	103	22023	37668
2027	411778	21924	110	23979	40495
2028	445303	23777	117	25996	43632
2029	479346	25666	123	28050	47098
2030	513583	27577	130	30113	50909

Unexpectedly, labor productivity has no significant effect on the value of gross agricultural output (GAO). Its coefficient is 0.055 and is statistically insignificant: t-value = 0.11, p = 0.735 – a very high p-value, indicating that this factor is not statistically significant. This result may be related to the level of technological development and mechanization.

The intercept (constant) of the regression equation is –2506.779, which suggests that if all independent factors are zero, GAO could be negative. From an economic interpretation perspective, this reflects a negative trend in the absence of key production factors. Based on the results of the correlation-regression analysis, econometric models were used to forecast the value of gross agricultural output, value added, and the share of agriculture in GDP, taking into account the conditional factors X1, X2, X3, and X4 for 2024–2030. In developing forecast indicators and calculating their dynamics, the author's proposals for improving sectoral development and economic relations in agricultural production were also considered (Table 5.3).

Conclusion. Based on the forecast data, the institutional changes implemented in the agrarian sector and the increasing integration with leading countries in the field indicate that attracting investments to the sector, financing research and innovation, and increasing the scale of government subsidies and support, along with the introduction of new incentives, will contribute to sustainable development in 2024–2030.

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OPTIMIZATION OF BUSINESS PROCESS OUTSOURCING

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Abstract. *This article examines the issues of optimizing business processes in a modern business environment using digital technologies. The research was conducted using a mixed methodology, analyzing a questionnaire survey with the participation of 248 enterprise representatives, in-depth interviews with 42 top managers, and 6 focus group discussions. During the study, successful practices were identified through observation and analysis of working documents. Scientifically based recommendations were developed, which provide for the gradual optimization of business processes, the development of digital competencies of employees, and the alignment of technological solutions with strategic goals.*

Keywords: *business process optimization, digital transformation, BPEI index, mixed methodology, operational efficiency, modern management,digital competence.*

INTRODUCTION

At a time when the pace of digitalization of the global economy is accelerating, business process optimization is considered a source of strategic advantage for enterprises. The problem of business process optimization occupies an important place in modern management, as it creates the opportunity to reduce operating costs, improve the quality of products and services, and quickly respond to customer needs.

Large-scale reforms being implemented in the Republic of Uzbekistan to develop the digital economy require the introduction of modern management technologies in the business sector. At the same time, the practice of optimizing business processes in local enterprises is still insufficiently studied, and scientifically based approaches are rarely used.The issues of improving business processes of enterprises and increasing their efficiency in the conditions of the modern economy are studied. During the study, the impact of the implementation of Lean management, Six Sigma methodologies and digital technologies (AI, RPA) on the activities of the enterprise was analyzed. An author's approach to eliminating them through Value Stream Mapping (VSM) is proposed. The results serve as a practical guide for business leaders and managers in optimizing the management system and reducing operating costs.

LITERATURE ANALYSIS

According to the McKinsey Global Institute, companies that effectively use digital technologies increase their competitiveness in the market by an average of 2.5 times. Foreign researchers, in particular Hammer and Champy, developed the concept of business process redesign, while Davenport analyzed innovative approaches. However, very few studies have been conducted specifically for Uzbek enterprises in the context of digital transformation. The purpose of the study is to develop scientifically based recommendations for the comparative analysis and practical implementation of business process optimization mechanisms in the context of digital transformation [1,2].

METHODOLOGY

The study was conducted in 2021-2024 using a mixed methodology. To collect quantitative data, a standardized questionnaire survey was conducted among 248 enterprise representatives, with respondents selected from various sectors (production 38%, trade 34%, service 28%). The survey questions were aimed at assessing the current state of business processes, the level of use of digital technologies, and the results of optimization. As a qualitative research component, semi-structured interviews were conducted with 42 senior managers, which helped to identify in-depth aspects and practical difficulties in optimizing business processes. In addition, 6 focus group discussions were held, each of which involved 8-10 specialists from different departments. The BPEI index was used to assess the efficiency of business processes, which allows for a comprehensive assessment of process speed, number of errors, resource consumption, and customer satisfaction. The Digital Maturity Assessment (DMA) test was used to measure the level of digital maturity, which rates companies into five levels: beginner (1-2 points), developing (3-4 points), intermediate (5-6 points), advanced (7-8 points) and leading (9-10 points). 12 successful practices (case studies) were studied through observation and analysis of working documents, and the results were statistically analyzed using SPSS Statistics 26.0. In order to ensure the reliability of the data, Cronbach's Alpha coefficient was calculated (α=0.89), which indicates high internal consistency.

DISCUSSION AND ANALYSIS

Overall research results and digital maturity analysis. The study showed that 34% of the respondent companies are at the initial stage of digital maturity, 41% are at the medium stage, and only 25% are at the high level. The average business process efficiency index of companies that have fully implemented digital transformation was 8.7 points (on a 10-point scale), while this indicator was 5.3 points for companies at the initial stage. These data indicate that there is great potential for increasing the level of digital maturity in local companies [3].

Table 1

Digital maturity level and business process efficiency

Digital maturity level	Number of enterprises	BPEI (average)	Reduce operating costs	Process speed increase
Elementary (1-2 points)	84 (34%)	5.3	8%	12%
Developing (3-4 points)	52 (21%)	6.4	15%	21%
Medium (5-6 points)	50 (20%)	7.2	23%	29%
Advanced (7-8 points)	42 (17%)	8.1	28%	35%
Leader (9-10 points)	20 (8%)	8.7	31%	43%

As the table shows, business process efficiency progressively improves as digital maturity increases. While entry-level enterprises reduced operating costs by only 8 percent, leading-edge enterprises achieved a 31 percent improvement. Similarly, process speed increased from 12 percent at the entry-level to 43 percent at the highest level [4].

Qualitative research findings and barrier analysis. The in-depth interview analysis identified a number of key barriers to business process optimization. The most common barrier is the lack of digital skills among employees, cited by 78 percent of respondents. High software costs are in second place (63 percent), and integration issues with legacy systems are in third place (54 percent). Additional barriers include a lack of support from senior management (47 percent), employee resistance to change (42 percent), and a lack of a clear strategy (38 percent).

During the focus group discussions, participants raised a number of important points. First, it was emphasized that active participation and ongoing support from top management are essential for successful optimization. Second, the need to develop a change management strategy was emphasized. As one focus group participant noted, the effectiveness of new systems decreases sharply if additional training programs are not organized for employees during the implementation of technological solutions. Third, it was emphasized that open communication about the reasons for the changes and the expected results is important [5].

Benchmarking and performance indicators. Business process optimization has yielded several significant results for companies. Operating costs have been reduced by an average of 31 percent, indicating more efficient use of resources. A 47 percent reduction in errors and defects confirms a significant improvement in quality indicators. A 38 percent reduction in time to market for products and services has been a significant factor in increasing competitiveness.

Table 2

Business process optimization efficiency across industries

Network	**Reduce operating costs**	**Error reduction**	**Time saving**	**Increased customer satisfaction**
Production	35%	52%	41%	28%
Trade	29%	43%	36%	34%
Service	28%	46%	37%	39%
Average	31%	47%	38%	34%

The table shows that business process optimization in different industries has yielded different results. The highest indicators were recorded in the manufacturing sector, which is associated with the characteristics of the industry. In the service sector, customer satisfaction increased to the highest level, which indicates the potential for improving service quality [6].

Analysis of successful practices. The 12 case studies reviewed revealed a number of common features. The companies that achieved the highest results used a step-by-step approach, automating simple processes first and then moving on to more complex ones. The first case study demonstrated the automation of order management in a manufacturing company. The process was reduced from 12 days to 5 days, and errors were reduced by 68 percent. The second case study optimized warehouse management in a trading company, which reduced inventory costs by 42 percent and provided real-time information about the availability of goods.

The third case study demonstrated the experience of digitizing customer service processes in the banking sector. As a result of the implementation of a mobile banking application, customer waiting times were reduced by 73 percent and service quality indicators improved by 56 percent. The fourth case study demonstrated the implementation of a route optimization system in a logistics company, which reduced fuel costs by 34 percent and shortened delivery times by 41 percent [7].

Statistical analysis results. Correlation analysis confirmed the existence of a strong positive correlation ($r=0.82$, $p<0.01$) between business process efficiency and digital maturity level. This is a highly statistically significant result. Regression analysis showed that each point increase in digital maturity level increases the BPEI index by an average of 0.64 points. This result proves the direct relationship between digital technologies and business process efficiency [8].

Another important finding identified during the study is that there is a nonlinear relationship between the size of the enterprise and the effectiveness of business process

optimization. Medium-sized enterprises (100-500 employees) showed the highest relative results, while small enterprises had resource constraints, while large enterprises had slightly lower effectiveness due to the complexity of integration.

Importantly, implementing technological solutions alone does not guarantee operational efficiency. The expected results will be achieved only if technologies are aligned with strategic goals and employees have the appropriate knowledge and skills. The results of the study showed that thorough preparation before implementing technologies, including process analysis, needs assessment, and staff training, is essential.

Further analysis revealed that the most successful companies have the following common characteristics: a system of clearly defined goals and indicators (92 percent), active support from top management (88 percent), employee involvement in change (85 percent), a continuous monitoring and evaluation system (81 percent), and a flexible approach (76 percent). This set of factors is the main condition for successful optimization [9]. Today, these methodologies are being integrated with Artificial Intelligence (AI) algorithms. The biggest bottleneck for Uzbekistan is the complexity of the decision-making chain and the paper-based formatting of data.

Synergy of RPA and AI: operational efficiency.

RPA and AI technologies are complementary manufacturing technologies, including:

RPA (System “Hands”) - management of quality mechanical tools for repetitive and rigid employees.

AI (the “brain” of the system) - analyzes complex, unstructured data and makes decisions based on predictions.

Table 3

Differences between RPA and artificial intelligence (AI)

Feature	**RPA (Robotic Process Automation)**	**Artificial Intelligence (AI)**
Basis	"If...then..." rules	Learning from data (Machine Learning)
Benefits	Speed and accuracy	Flexibility and in-depth analysis

Today, these methodologies in the economy have reached a new level. Now, waste is detected not by the human factor, but by Artificial Intelligence (AI) algorithms. The “bottleneck” observed in the experience of Uzbekistan is the excessive internalization of the decision-making chain and the paper form of information [10].

Table 4

RPA and AI Synergy: The New Driver of Operational Efficiency

Feature	**RPA (Robotic process automation)**	**Artificial Intelligence (AI)**
Task	Copy and repeat processes	Simulating human intelligence
Basis	"If...then..." rules	Learning from data (Machine Learning)
Benefits	Speed and accuracy	Flexibility and in-depth analysis

Research shows that in many cases, the components of RPA (Robotic Process Automation) and AI are confused, which is why the court considers their role in the business process to be different:

RPA (System “Hands”) - trepetitive, persistent human risk factors (e.g., monitoring reports, moving data from one database to another).

AI (The “brain” of the system) -analyzes complex, unstructured data, makes predictions, and assists in decision-making.

The study used the Value Stream Model (VSM) methodology to identify waste in business processes. VSM visualizes all stages of a product or service from the raw material stage to the final consumer.

Current status (Current status) - mwith data validation "traffic jams", escalation factors, and human-related delays.

Future State -IA (RPA + AI) inspection is integrated, creating an ideal process free of "muda" (waste) models.

Value Stream Mapping (VSM) was used to identify waste in business processes in the Value Stream Improvement Methodology (VSM):

Current status (Current status) - delays caused by "traffic jams" and human factors in the installation of information.

Future State - Intelligent Automation (IA) creates an ideal process model free of risk and waste[11].

CONCLUSION

The following scientifically based recommendations are provided to enterprises.

First, it is necessary to develop a business process optimization strategy and integrate it into the overall corporate strategy, which should include clear goals, indicators and an implementation roadmap.

Second, it is important to introduce programs for developing digital competencies of employees and actively manage the fight against change, for this purpose it is recommended to organize regular trainings, webinars and practical exercises.

Third, it is advisable to use a step-by-step approach, first gaining experience by optimizing simple processes and then moving on to more complex ones.

Fourth, it is necessary to introduce a standardized indicator system, such as BPEI, for regular monitoring of the effectiveness of business processes, which will allow for an objective assessment of the effectiveness of changes and timely adjustments.

Fifth, when choosing technological solutions, it is necessary to take into account the specific needs and strategic goals of the enterprise, and not blindly copy ready-made solutions. Sixth, it is necessary to involve all stakeholders, including executive staff, in business process optimization projects, which will allow using their experience and reducing resistance to change.

The digital maturity level of enterprises was assessed based on the Business Process Efficiency Index (BPEI). The results showed that enterprises that fully integrated digital technologies saw a 43% improvement in business process efficiency and a 31% reduction in operating costs.

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DIRECTIONS FOR THE DEVELOPMENT OF WOMEN'S ENTREPRENEURSHIP IN UZBEKISTAN

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Abstract. *This article systematically studies the process of developing women's entrepreneurship in Uzbekistan. The research analyzes the economic and social significance of women's entrepreneurship, the factors affecting its development, and existing challenges. Using a SWOT analysis, the strengths and weaknesses of the sector, as well as opportunities and threats, were identified. Additionally, the study illustrates the growth in the number of women entrepreneurship entities with a graph, presents research hypotheses, and conducts analyses based on economic data. Based on the research findings, practical proposals and recommendations have been developed to further promote women's entrepreneurship. The results enable the formulation of actionable strategies to enhance the development of women entrepreneurs.*

Keywords: *women's entrepreneurship, small business, economic activity, family income, women's employment, private entrepreneurship, gender equality.*

INTRODUCTION

In Uzbekistan, the development of women's entrepreneurship has in recent years become an important component of state policy. Entrepreneurship involving women not only increases economic activity, but also provides a strong impetus for enhancing social stability in society and strengthening the economic well-being of families. Actively engaging women in economic processes contributes to the formation of a modern model of a market economy.

According to Presidential Decree No. PF-50 of March 25, 2025, issued by the President of the Republic of Uzbekistan, a comprehensive system for the development of women's entrepreneurship is to be introduced. This includes identifying proactive women who lack business skills and providing them with entrepreneurship training, assisting in the preparation of business projects and the establishment of small enterprises, and working individually with the most active and rapidly growing businesswomen to transform them into "champion" entrepreneurs (Fozilova, 2025).

As emphasized by Shavkat Mirziyoyev, the "New Uzbekistan Development Strategy" identifies the creation of decent conditions for women and the support of their initiatives as one of its priority directions. Based on the experience gained during the implementation of this initiative and the results of public discussions, the "Uzbekistan–2030" Strategy was developed. The "Uzbekistan–2030" Strategy outlines measures to support women's entrepreneurship, ensure their legal rights and interests, increase their social, economic, and political participation, and promote gender equality (Kamoldinova, 2024).

Today, the development of women's entrepreneurship in Uzbekistan is considered one of the strategically significant tasks. According to data from the World Bank, the advancement of women's entrepreneurship can lead to an average increase of 3–4 percent in a country's gross domestic product.

LITERATURE REVIEW

The fate of a nation and the assurance of a bright future for a country largely depend on the role of educated and enlightened women. The French writer Honoré de Balzac once emphasized this idea, stating: “The future of a nation is in the hands of mothers.” Contemporary research and family observations indicate that in households where women are wise, refined, fair-minded, and educated, individuals with strong moral and spiritual values are more likely to be raised (Uraimjonova, 2023).

A number of foreign and domestic economists have conducted research on women’s entrepreneurship. Russian economist Alimpiyeva examined the strategic characteristics of women in entrepreneurship and the impact of entrepreneurial activity on family life. In the studies of Semenov and Raymanova, factors negatively affecting the development of women’s entrepreneurship were analyzed. According to another scholar, Semyonova, highly educated middle-aged and older women tend to achieve higher results in entrepreneurial activity. She emphasizes that in establishing and developing their own businesses, such women effectively utilize necessary financial resources and networks, while demonstrating high professional competence, managerial experience, independent creative approaches, and initiative (Burxanova, 2025).

Women’s entrepreneurship is defined as businesses managed by women. This term first appeared in the works of researchers in the United States and Europe in the 1930s. By the late 20th and early 21st centuries, the concept began to be widely used in national academic literature, particularly in mass publications. In the late 1980s and 1990s, scholars such as I.E. Kalabikhina, G.N. Karelova, and Z.A. Khotkina explored the economic perspective that women’s employment and living standards could be improved through small business and entrepreneurship (Kamoldinova, 2024).

The results of the literature review indicate that in Uzbekistan, the development of women’s entrepreneurship has increasingly become a key direction of economic policy in recent years. Analytical data show that over the past five years, the steady growth in the number of enterprises led by women reflects the relative effectiveness of state support measures in this sphere. However, the growth rates are not uniform across regions. In particular, the slower development of women’s entrepreneurship in rural areas highlights the issue of economic imbalance.

RESEARCH METHODOLOGY

This study examines the process of developing women’s entrepreneurship in Uzbekistan. The selected methodology made it possible to assess the current state of women’s entrepreneurship, identify existing challenges, and formulate practical conclusions. A comprehensive methodological approach was applied in the research. The multifactorial nature of the research object—namely, the close interconnection of women’s entrepreneurship with financial, social, regional, and institutional aspects—required the use of multiple methods rather than reliance on a single approach.

During the research process, the most dynamically developing sectors of women’s entrepreneurship were identified, along with the age-related activity patterns of women entrepreneurs. In these areas, women entrepreneurs demonstrated strong adaptability to market demand and a high level of initiative as key competitive advantages. Based on a regional analysis, disparities in the development of women’s entrepreneurship were identified, and these differences were interpreted in relation to the effectiveness of regional policies and support mechanisms.

The study also revealed that sustainability in entrepreneurial activity is more closely associated with knowledge, experience, and institutional support than with the mere volume of financial resources. As a result, it is substantiated that, alongside financial assistance, expanding educational programs, advisory services, and mentorship mechanisms is essential for the sustainable development of women's entrepreneurship.

ANALYSIS AND RESULTS

Scientific studies and statistical data collected in Uzbekistan clearly demonstrate the socio-economic significance of women's entrepreneurship. As of January 1, 2025, the number of small enterprises and microfirms headed by women reached 43,860, reflecting growth compared to 2024. The majority of women-led businesses operate in the service and trade sectors, and their total revenues have increased substantially. According to a recent report by the United Nations Development Programme (UNDP), in 2024 the number of women actively engaged in entrepreneurship in Uzbekistan reached 2.1 million, which is seven times higher than in 2020. The report emphasizes that state policies, financial programs, and social support systems have played a crucial role in achieving this growth.

Various factors influence the development of women's entrepreneurship. Limited access to financial resources, insufficient business knowledge and skills, family responsibilities, and persistent gender stereotypes are identified as major barriers. At the same time, the expansion of digital technologies and educational programs has become a significant supportive factor for women's businesses. Women's entrepreneurship is important not only for economic growth but also for strengthening social stability. Businesses established by women contribute to increased employment and improved household welfare, thereby generating broader socio-economic benefits.

SWOT ANALYSIS

Analyzing the current state of women's entrepreneurship development in Uzbekistan, the following strengths, weaknesses, opportunities, and threats can be identified.

Strengths: Women's entrepreneurship demonstrates several positive features. In particular, women's diligence, responsibility, and initiative constitute significant competitive advantages. Moreover, state-supported microloans, preferential grants, and specialized business training programs designed for women contribute to the establishment and expansion of entrepreneurial activities. These support mechanisms play an important role in enabling women to start and manage their own businesses successfully.

Weaknesses: Despite these advantages, certain weaknesses persist. Many women have limited access to sufficient financial resources, which constrains business expansion. In addition, low levels of digital literacy and a lack of entrepreneurial experience create obstacles for many women. These factors limit the sustainability and long-term growth potential of their enterprises.

Opportunities: There are considerable opportunities for further development. Through the expansion of the digital economy and online platforms, women can broaden the scope of their businesses and access wider markets. Furthermore, foreign investments, international grant programs, and ongoing state support policies create favorable conditions for launching and scaling women-led enterprises.

Threats: However, several threats remain. Increasing market competition, persistent gender stereotypes, and social constraints may hinder women's entrepreneurial activities. Additionally, complexities within the legal and tax systems can create further challenges in business development and formalization.

Table 1.

Key Economic Indicators of Women's Entrepreneurship in Uzbekistan

Years	**Women's Entrepreneurship Entities**	**Allocated Credits (billion soums)**	**Employment (thousands of people)**
2019	215	4 800	680
2020	228	5 600	710
2021	245	7 200	760
2022	268	9 500	820
2023	295	12 300	890

Source: *Compiled based on official statistical data of the Uzbekistan.*

The data in Table 1 indicate that during 2019–2023, the number of women-led business entities in Uzbekistan showed a steady upward trend. Specifically, this figure increased from 215,000 in 2019 to 295,000 in 2023, demonstrating the effectiveness of government support measures. If we represent this economic example visually in the form of a chart based on these numbers, it would appear as follows:

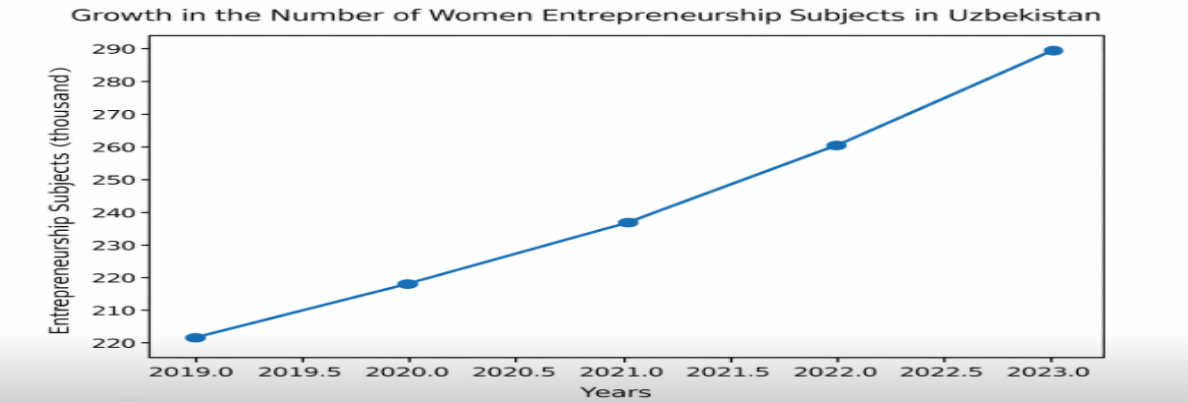


Figure 1. Growth dynamics of the number of women-led business entities in Uzbekistan during 2019–2023.

Source: *Based on data from the Statistics Agency of the Republic of Uzbekistan.*

The data presented in the figure indicate that during 2019–2023, the number of women-led business entities in Uzbekistan followed a steady upward trend. In particular, this indicator increased from 215,000 units in 2019 to 295,000 units in 2023. This trend demonstrates the effectiveness of institutional and financial mechanisms aimed at supporting women's entrepreneurship and reflects the growing economic activity within this sector.

At the same time, statistical data show that although women's entrepreneurship is expanding, a gender gap still persists. For example, in the field of information and communication technologies (ICT), only about 10.6% of enterprises are managed by women, and female participation in innovative sectors remains comparatively low. From a theoretical perspective, women's entrepreneurship contributes not only to economic growth but also to gender equality, social stability, and employment generation. This is supported not only by the theory of micro and small business development, but also by state policy frameworks and gender economics concepts. Businesses established by women increase household incomes, create new jobs, and strengthen gender equality in society.

In 2022, more than 95,000 women who expressed the desire to start entrepreneurial activities were officially registered as entrepreneurs, and to date, these women have created nearly

184,000 new jobs. Over the past five years, the number of businesswomen in Uzbekistan has doubled, with more than 205,000 women successfully launching their own enterprises. In 2023, over 13 trillion soums in credit were allocated to more than 279,000 entrepreneurial projects, and nearly 300 billion soums in subsidies were provided to approximately 57,000 women. In addition, around 200,000 women received vocational and entrepreneurship training. Most importantly, more than 400,000 women were provided with employment opportunities (Saidova, 2025).

Research Hypotheses

1. If support mechanisms for women's entrepreneurship are implemented effectively, women's economic activity will increase significantly.
2. Improved access to financial resources has a positive impact on the sustainable development of women's entrepreneurship.
3. The use of digital technologies and online platforms facilitates the establishment and management of businesses in women's entrepreneurship.
4. State programs aimed at developing women's entrepreneurship contribute to increased employment and higher household incomes in Uzbekistan.
5. Expanding education, advisory, and information services enhances the competitiveness of women's entrepreneurship.

CONCLUSION

This article systematically examined the current state of women's entrepreneurship development in Uzbekistan, its economic significance, and existing challenges. The key factors affecting the sustainability of women's entrepreneurial activity were identified, and their impact on both short- and long-term outcomes was evaluated. In particular, the study scientifically highlighted the differences between challenges encountered at the business startup stage and obstacles arising during business development, emphasizing the critical role of knowledge and skills in women's entrepreneurial activities.

The research results indicate that women's entrepreneurship is a vital component of the country's economy and social stability. Women-led business entities primarily operate in the service and trade sectors and play an important role in increasing employment and household incomes. Although there are significant positive trends in the development of women's entrepreneurship in Uzbekistan, several challenges persist. Limited access to financial resources, insufficient business knowledge and experience, and social and institutional barriers remain key factors that reduce the effectiveness of women's entrepreneurial activity.

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IMPROVEMENT OF ORGANIZATIONAL AND LEGAL BASES OF FOREIGN ECONOMIC ACTIVITY

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Abstract*. Protection of the domestic market is one of the most important areas of the state's influence on the economy. Along with the defense capability of Uzbekistan, it is important to have the competitiveness of goods. To achieve this goal, it is necessary to create a strong industrial base in the country, create a legal infrastructure, establish strong legal relations with the economy of foreign countries, and protect productive sectors of industry from unfair competition of foreign companies. One of such protective measures is measures to protect the internal market of goods in the implementation of foreign economic activity. In this mechanism, anti-dumping, compensation and special protection measures introduced by the government of Uzbekistan play a key role.*

Keywords*: currency control, tax control, customs control, dumping, anti-dumping and regulation.*

Introduction

In the general sense, the legal mechanism in this area is, first of all, a set of management tools by which scientifically based management decisions are made and their effective implementation is achieved. The essence of the mechanism is that it combines the main elements of management and acts as an organizational tool, a single management tool for making and implementing management decisions. Consequently, the administrative and legal regulation of foreign economic activity proceeds from the creation and provision of conditions for society to operate on the basis of current regulatory and legal documents. The basis for the implementation of these processes is the changes taking place in Uzbekistan, which attempts to comprehensively study the state and development of administrative and legal regulation of foreign economic activity in Uzbekistan using the example of the main elements of this activity. The relevance of the research is also determined by the fact that the system of state regulation of foreign economic activity of the Republic of Uzbekistan is currently being improved.

The need to improve the organizational legal framework is due to the fact that many issues of applying measures to protect the domestic market in this activity are not regulated by the relevant legal relations. Effective national legislation in the field of applying measures to protect the domestic market of goods in the implementation of state management of foreign economic activity, if studied and applied only in the part that corresponds to the interests of the domestic economy, will create mechanisms for protecting the domestic market with specific national characteristics. Currently, it is possible to take measures to protect the domestic market in the implementation of foreign economic activity by implementing restrictive measures to protect the domestic market of goods.

The application of measures to protect the domestic market in the implementation of foreign economic activity has international legal, constitutional legal, administrative legal, financial legal and economic legal aspects. In order to prevent the one-sidedness of the legal

sphere, it is necessary to combine the efforts of many legal scholars in the study of such a law institute. Their dissertations should begin with an understanding of the legal essence of the above-mentioned measures and the principles of their application. At the same time, it is impossible not to take into account the approach developed over the years in the analysis of the administrative activity of the state in implementing market protection, since the activities of the executive authorities in this area have a clearly administrative nature.

Measures to protect the domestic market in the implementation of foreign economic activity are also a source of negotiation for the foreign trade policy of Uzbekistan. The state plays a special role in the development of foreign economic activity. It is precisely high-quality management of foreign economic activity that allows us to achieve the main goal of modern regulation of Uzbekistan's foreign economic activity - its integration into the world economy. Effective integration is based on such management.

In the Decree No. PF-158 dated September 11, 2023 on the STRATEGY “Uzbekistan - 2030”, our President Sh. Mirziyoyev also stated that foreign economic activity should be considered as part of the state's foreign policy, as well as the national economic policy, therefore it should be regulated by the state, and the mechanism of legal regulation of foreign economic activity, primarily the use of various legal instruments that perform specific functions in the system of legal regulation of foreign economic relations, should be brought to new levels as the main task. Protectionist measures are aimed at directly restricting exports and imports in order to protect certain national industries, for example, quotas and licensing, export controls, and import safeguards. Administrative measures restrict foreign economic activity by setting technical, sanitary, and environmental standards for imported goods, and price preferences are eliminated.

Currently, states are developing a system of administrative and legal regulation of foreign economic activity. In general, there are about a hundred state intervention measures in the world. In general, they can be divided into the following groups:

1. Economic measures:
- export and production subsidies;
- anti-dumping duties;
- import deposits;
- exchange rate regulation;
- export and import taxes, excise duties;
- compulsory sale of part of foreign currency earnings;
- system of state orders;
- financing of research;
- nationalization/privatization of property.

2. Technical measures:
- requirements for compliance with national standards;
- quality acceptance, certification;
- sanitary and environmental standards;
- safety standards.

3. Administrative regulatory measures:
- customs tariffs;
- currency control;
- declaration of goods;
- embargo;

- quotas, quotas;
- licenses;
- directive setting of contract prices;
- restrictions on types of foreign trade operations.

Foreign economic activity is understood as a separate specific type of activity of economic entities. Each enterprise carries out this activity independently, based on the choice of a foreign market. This is foreign trade, investment and other activities in the field of international exchange of goods, information, works, services, results of intellectual activity, rights to the results of intellectual activity. This activity also includes production cooperation in these areas. Legal regulation of foreign economic activity in Uzbekistan and in other countries is based on the state monopoly of foreign trade. Foreign economic activity is reflected in international and our state practice in various forms and types. Foreign experience identifies the following types of foreign economic activity:

- foreign trade activity;
- production cooperation;
- currency and financial and credit operations;
- relations with international organizations.

Foreign trade activity is one of the most widespread areas of foreign economic activity. Transactions on such activities are formalized by foreign trade agreements. Agreements are divided into import-export, leasing, investment, financial and other types. Foreign economic activity contracts are concluded in foreign currency and are carried out in accordance with international rules. The following forms of foreign trade activity are distinguished: a) export transactions; b) import transactions; c) barter transactions.

Research methodology

Foreign trade is one of the most widespread areas of foreign economic activity. Transactions on such activities are formalized by foreign trade agreements. Agreements are divided into import-export, leasing, investment, financial and other types. Contracts on foreign economic activity are concluded in foreign currency and are carried out in accordance with international rules. The following forms of foreign trade activity are distinguished: a) export transactions; b) import transactions; c) barter transactions. In most sources discussing foreign economic activity, this area of social relations operate as a subsystem of the economy. As a result, economic concepts form the basis of the concepts used in foreign economic activity. Therefore, not only the definition of “foreign economic activity” is often used, but the general definition is “foreign economic sphere”.

At the same time, when it comes to the foreign economic sphere, a very wide range of concepts is used. Each of them has a certain status, which depends on the place occupied by this concept in the subsystem under consideration. The following concepts are basic and occupy a special place in the field of foreign economic activity: foreign economic activity, foreign trade activity, foreign economic relations. It is very important that these concepts are not differentiated in modern legislation, but are hierarchically interconnected, while not losing their main ability - the property of being integral. Foreign economic activity includes such processes as the exchange of goods and services between states, the movement of capital and labor, the spread of technologies and knowledge. At the same time, foreign economic activity depends not only on economic changes, but also on political, social and environmental factors. States use various legal forms to regulate foreign economic activity in implementing their economic policy.

Analysis and results. Currency legislation for regulating foreign economic activity includes a number of legal mechanisms, norms and standards. Through these mechanisms, states manage trade and investment activities. Ensuring exchange rate stability is one of the most important tasks of currency legislation. Strong fluctuations in the national exchange rate can complicate foreign economic activity and disrupt trade relations. Therefore, states manage foreign trade and investment by managing the exchange rate. Some countries freely determine the exchange rate of their national currency based on market supply and demand. Through such a system, the exchange rate adapts to the state of the national economy. Some countries stabilize it by intervening against sharp fluctuations in the exchange rate. This is usually done by central banks and is done in order to support the market. Capital movement management is another important task carried out through currency legislation. States try to maintain the stability of the national economy by controlling capital flows.

Capital outflow and inflow: Some countries regulate the outflow of capital abroad or the inflow of capital from abroad with restrictions. This is mainly aimed at ensuring economic stability and maintaining foreign exchange reserves. Through currency legislation, countries can provide tax breaks and other incentives to attract foreign investment. This, in turn, ensures economic growth and job creation. Through currency exchange management, countries try to protect the domestic market and normalize foreign economic relations. Currency legislation is mainly aimed at controlling and regulating transactions carried out in the foreign exchange market. Restrictions on foreign exchange transactions: Some countries may regulate foreign exchange transactions with special restrictions. For example, licenses may be required to buy or sell certain currencies. Foreign exchange reports: Companies and organizations engaged in foreign economic activities may be required to submit special calculations.

Through this, countries have the opportunity to verify the correctness of international trade transactions. Currency law provides countries with international mechanisms for regulating international trade and investment. Through this, economic relations between countries are coordinated and standardized. Currency transactions and capital movements are governed by trade agreements and investment treaties concluded between countries. For example, international organizations such as the United Nations (UN) and the World Trade Organization (WTO) set standards related to currency law. International currency agreements: International agreements are concluded to coordinate currency exchange and capital flows between countries. These agreements are mainly implemented to manage exchange rates, encourage foreign investment, and regulate international financial systems. Currency law serves as an important tool in regulating foreign economic activity. It creates the necessary legal mechanisms to manage countries' foreign trade, capital flows, and exchange rate operations.

Through currency legislation, states help ensure their economic security, coordinate their international economic relations and maintain economic stability, and the existing legislation has only created a new basis for the development and restructuring of currency regulation and currency control. However, it is impossible to implement it without a deeper study of the theoretical foundations of legal regulation of currency relations, based on domestic and foreign experience. It is necessary to establish alternative and relatively clear sanctions that allow individualizing financial responsibility, and financial sanctions should be regulated not only at the level of departmental regulatory documents, but also at the level of laws. All this will allow the Republic of Uzbekistan to become a full member of the international economic community.

Conclusions and recommendations. Laws and regulations regulating foreign economic activity in administrative management are important for ensuring the country's economic security, attracting foreign investment and developing foreign trade.

Regulatory mechanisms: Updating and strengthening the rules regulating foreign economic activity. This increases the state's ability to manage all processes related to foreign economic activity.

Openness and transparency: Publicly disclosing information on foreign trade operations and agreements. This improves the business environment and increases investor confidence.

Analysis and monitoring: Introducing special monitoring systems to monitor and analyze foreign economic activity. This allows for timely identification of negative trends.

Personnel training: Training qualified personnel in the field of foreign economic activity and updating their knowledge. This helps to improve control and management processes.

Investment support: Creating special programs and incentives to attract foreign investment. This makes it easier for foreign companies to enter our country.

Constantly updating and adapting the legislation on foreign economic activity to modern requirements and standards. It is necessary to strengthen cooperation with international economic organizations and other countries, exchange experiences, and jointly develop new regulatory mechanisms.

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MODERN METHODOLOGICAL APPROACHES TO ASSESSING ECONOMIC SECURITY IN INDUSTRIAL ENTERPRISES AND THEIR PRACTICAL APPLICATION

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Abstract*. This article analyzes modern methodological approaches to assessing the economic security of industrial enterprises. An integral evaluation model based on financial, production, and profitability indicators is proposed. Using oil and fat industry enterprises as examples, the level of economic security is assessed, key problems are identified, and improvement directions are substantiated.*

Keywords*: Economic security, industrial enterprise, evaluation methodology, integral index, financial stability, profitability, liquidity, risk management, innovation, competitiveness, production efficiency, management, monitoring, analysis, model.*

Introduction

In the modern economic environment, the sustainable development of industrial enterprises depends on numerous internal and external factors, one of the most critical of which is economic security. The deepening of market relations, intensifying global competition, volatility in resource prices, and the growing level of financial risks have increased the degree of uncertainty in enterprise operations. Therefore, ensuring and accurately assessing economic security has become one of the most pressing scientific and practical challenges.

Traditional assessment methods mainly rely on financial indicators; however, this approach is no longer sufficient in today's conditions. Contemporary methodologies consider economic security as a comprehensive system and require the integrated analysis of production efficiency, profitability, liquidity, and risk factors. This article examines modern approaches to assessing economic security in industrial enterprises and analyzes their effectiveness based on practical examples.

Literature Review. In *Digital Marketing: Strategy, Implementation and Practice*, Dave Chaffey analyzes methods for enhancing enterprise performance through digital marketing strategies and innovative approaches, emphasizing their importance in strengthening economic security [1; p.79]. In *Enterprise Risk Management*, John Fraser and Betty Simkins examine the risk management system and its integration with corporate strategy, developing theoretical foundations for the comprehensive assessment of economic security [2; p.71].

In *Fundamentals of Risk Management*, Paul Hopkin provides an extensive discussion of methods for identifying, assessing, and managing risks, which serve as an important methodological basis for ensuring economic security in industrial enterprises [3; p.63]. The International Organization for Standardization document *ISO 31000 Risk Management Guidelines* outlines international standards for risk management and serves as a universal methodological framework for assessing economic security [4; p.7].

In *The Balanced Scorecard*, Robert Kaplan and David Norton develop a comprehensive model for evaluating enterprise performance through the integration of financial and non-financial indicators, which is highly relevant for monitoring economic security [5; pp.48–60]. In *Managing Risks: A New Framework*, Robert Kaplan and Anette Mikes propose a new model for classifying and managing risks, highlighting theoretical approaches that enable effective identification and mitigation of risks within enterprises [6; pp.71–79].

In *Marketing Management*, Philip Kotler discusses market strategies and ways to enhance competitiveness to ensure enterprise sustainability, revealing their close interconnection with economic security [7; p.261]. In the study *Assessment of Economic Security of Enterprises*, S. Shynkar develops both theoretical and practical approaches to evaluating enterprise economic security and proposes an integral indicator model [8; pp.261–271].

In the research *Econometric Modeling of Economic Security in Industrial Enterprises*, Akbarxon Toxirov develops an econometric model for assessing the economic security of enterprises, substantiating its effectiveness through practical calculations [9; pp.61–69]. In *Enterprise Economic Security*, N. Vanesova systematizes the theoretical foundations and structural elements of economic security, providing an important methodological framework for enterprises [10; pp.98–102].

Discussion. The assessment of economic security in industrial enterprises is an essential component of modern management systems. Economic security refers to an enterprise's ability to withstand internal and external threats, maintain financial stability, ensure continuity of production processes, and strengthen its market position. In this study, a comprehensive approach was applied to the evaluation of economic security, since a single indicator cannot fully reflect the overall condition of an enterprise. This is particularly relevant for oil and fat industry enterprises, where debt burden, liquidity, profitability, and asset utilization efficiency are closely interrelated. The model selected for this research is an integral assessment model, which allows multiple indicators to be combined into a single index. The model is expressed by the following general formula:

$$IES \quad = \sum_{i=0}^{n} wi * Ni$$

Where:

IES — integral index of economic security;

wi — weight coefficient of the i-th indicator;

Ni — normalized value.

Normalization is carried out in two ways. If a higher value of an indicator is considered positive, the following formula is applied:

$$Ni = \frac{\text{Xi}}{\text{Xmax}}$$

If a lower value is preferable (for example, in the case of the debt ratio), the following formula is used:

$$Ni = \frac{\text{Xi}}{\text{Xmin}}$$

The following key indicators were selected for the study: debt ratio, current ratio, quick ratio, total asset turnover, net profit margin, and return on assets (ROA). These indicators reflect the enterprise's financial stability, its ability to meet short-term obligations, efficiency in the use of assets, and overall profitability. The weight coefficients were assigned as follows: debt ratio —

0.20; current ratio — 0.20; quick ratio — 0.15; total asset turnover — 0.15; net profit margin — 0.15; ROA — 0.15.

The advantage of this model lies in its ability to integrate various aspects of enterprise performance into a single system and to enable comparative analysis across different enterprises. At the same time, since some indicators in the dataset are presented on different scales across years, it was considered appropriate to interpret them using relative and comparative analysis methods. As a result, the model serves not only as a theoretical framework but also as an effective practical tool for determining the level of economic security of enterprises.

Results. In the empirical part of the study, data from three enterprises — "Kattaqorgon Oil and Fat" JSC, "Koson Oil Extraction" JSC, and "Kogon Oil Extraction Plant" JSC—were analyzed. Although the data covered different periods, the indicators for 2020, which were available for all enterprises, were selected as the base year for comparative analysis. This approach made it possible to evaluate differences across enterprises within the same time frame.

Table 1. Comparative analysis of key indicators for 2020

Enterprise Name	Debt Ratio	Current Ratio	Quick Ratio	Total Asset Turnover	Net Profit Margin	ROA
Kattaqorgon Oil and Fat JSC	520.0	–	–	2.04	-12.31%	-25.09%
Koson Oil Extraction JSC	82.75	950.0	370.0	1.85	13.35%	24.72%
Kogon Oil Extraction Plant JSC	35.58	1.95	660.0	1.78	0.07%	0.12%

The results indicate significant disparities among the enterprises. At Kattaqorgon Oil and Fat JSC, the extremely high debt ratio, along with negative net profit margin and return on assets, suggests a serious decline in economic security. The trend line shows a downward trajectory after 2018: net profit shifted from positive values in 2018 to losses in 2020, followed by increasing instability in subsequent years. Net income also declined sharply after 2020. Thus, according to the model, this enterprise falls into the "high-risk zone".

Koson Oil Extraction JSC, on the other hand, demonstrated relatively stable performance. In 2020, net profit amounted to 13.87 billion UZS, with a net profit margin of 13.35% and ROA of 24.72%. Trend analysis indicates that profitability generally followed an upward trajectory during 2015–2020. Although total asset turnover slightly decreased compared to 2018, financial performance remained positive, indicating efficient resource utilization. According to the model, this enterprise is close to a "stable condition."

Kogon Oil Extraction Plant JSC exhibited an intermediate position. While profitability was relatively high during 2015–2018, net profit declined sharply in 2020–2021. The net profit margin dropped to 0.07%, and ROA to 0.12%. These indicators suggest that although the enterprise maintained production and sales volumes, it experienced a decline in profitability. Despite the growth in total assets, decreasing profitability negatively affected its economic security.

Overall, the results show that the model allows enterprises to be classified into three groups: high-risk, moderately unstable, and relatively stable. This confirms the practical relevance of the integral approach. Graphical and trend analyses, particularly for net profit, net income, and ROA, clearly illustrate the development trajectories of enterprises. Based on this, short-term

forecasts indicate increasing risks for Kattaqorgon, the need for recovery measures for Kogon, and the necessity of maintaining stability for Koson.

Conclusion. This study demonstrates the practical significance of modern methodological approaches to assessing economic security in industrial enterprises. Based on the integral assessment model, data from three oil and fat industry enterprises were analyzed, revealing significant differences in their levels of economic security. In particular, financial stability, liquidity, asset turnover, and profitability were identified as key determinants of overall economic security. The analysis shows that the level of economic security at Kattaqorgon Oil and Fat JSC has declined due to negative profitability and increasing debt burden.

Koson Oil Extraction JSC stands out as a relatively financially stable enterprise. Meanwhile, although Kogon Oil Extraction Plant JSC has maintained its production capacity, the decline in profitability has weakened its level of economic security. Accordingly, to enhance economic security, enterprises should optimize their debt burden, restore profitability, improve asset utilization efficiency, and strengthen financial monitoring systems. The integral model serves as an effective scientific and practical tool for conducting such analyses in a systematic and comparative manner.

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METHODOLOGY FOR ASSESSING THE ECONOMIC SECURITY AND COMPETITIVENESS OF ENTERPRISES BASED ON THE INNOVATION MARKETING INDEX

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Abstract*. This article studies the role of the innovative marketing factor in ensuring the economic security and increasing the competitiveness of enterprises. As part of the research, an integrated indicator for assessing innovative marketing activities at enterprises, the innovative marketing index (IMI), was developed. The results of the study showed that the economic stability and competitiveness of enterprises increase as the level of use of innovative marketing tools increases.*

Keywords*: innovative marketing, economic security, competitiveness, IMI, digital marketing, CRM, SMM, artificial intelligence, enterprise management.*

Introduction

The rapid transformation of business models and technologies, along with the shortening of product life cycles, clearly demonstrates that it is impossible to enhance enterprise competitiveness without the use of innovations. Enterprise competitiveness reflects its superiority over rival firms producing similar products within the same field of activity. One of the key ways to ensure the economic security of an enterprise and to increase its competitiveness is the development of innovative ideas and their practical implementation. Moreover, the continuous changes in competitive conditions are increasing the necessity of applying innovations in marketing.

In crisis situations, producing goods based on consumer needs enhances the competitiveness of an enterprise in the market and compels it to operate more efficiently. Research shows that when financial constraints limit technological innovation, innovative marketing becomes a primary tool in competitive struggle. The performance of an enterprise in the market environment is determined by its customers. If customers value the company’s products and services more than the costs incurred to produce them, the business will grow; otherwise, it will require external support or may face decline.

Literature Review and Methodology

Scientific sources on the role and importance of the innovative marketing index in ensuring economic security were analyzed. Based on Uzbek and international academic literature, including research articles and monographs, theoretical foundations were developed regarding the impact of innovative marketing on economic security. In addition, various approaches and concepts related to economic security were examined. In *CRM and Customer Value*, Adrian Payne explains the mechanisms for increasing customer value and building loyalty through CRM systems, which serve as a key foundation for the CRM component of the IMI index [1; p.7].

In the article *Econometric Modeling of Economic Security in Industrial Enterprises*, Akbarxon Toxirov discusses the importance and relevance of econometric modeling in ensuring

the economic security of industrial enterprises [2; pp.61–69]. In *Digital Marketing: Strategy, Implementation and Practice*, Dave Chaffey examines digital marketing strategies and their implementation mechanisms, highlighting their importance for substantiating the Digital Marketing (DM) component of the IMI index [3; p.7].

In *Artificial Intelligence in Marketing*, Thomas Davenport and co-authors analyze AI-based marketing tools (such as predictive analytics and targeting) and their impact on business performance, providing a foundation for the AI component of the IMI index [4; pp.24–42]. In *Users of the World, Unite!*, Andreas Kaplan and Michael Haenlein analyze the role of social media in marketing and its impact on corporate strategy, forming the theoretical basis for the SMM component of the IMI index [5; pp.59–68].

In *The Balanced Scorecard*, Robert Kaplan and David Norton develop a comprehensive system for evaluating enterprise performance, providing methodological justification for using the IMI index as a KPI [6; p.7]. In *Marketing 4.0: Moving from Traditional to Digital*, Philip Kotler describes the transition of marketing from traditional forms to digital and interactive formats, explaining how innovative marketing tools (such as SMM, digital platforms, and customer engagement) enhance enterprise performance [7; p.7].

In *Marketing Management*, Philip Kotler and Kevin Lane Keller provide a comprehensive analysis of marketing management, branding, customer relationships, and digital strategies, serving as a key source for understanding IMI components such as CRM and branding [8; p.7]. In *Market Orientation and Performance*, Tomas M. Hult and co-authors analyze how market orientation and marketing innovation affect firm performance, which is important for explaining the relationship between the IMI index and economic security [9; pp.117–132].

In *Competitive Advantage*, Michael Porter examines the mechanisms for achieving competitive advantage, scientifically substantiating the role of marketing strategies in ensuring stability and security [10; p.7]. In *The Impact of Innovation on Firm Performance*, Vesna Zabkar and co-authors empirically demonstrate that innovations (including marketing innovations) have a positive impact on firm performance and competitiveness [11; pp.589–597].

Discussion. According to the research findings, innovative marketing is associated with the development of new products, equipment, services, and technologies, as well as the use of new marketing methods for their commercialization. Based on the analysis of enterprise activities, the use of innovations in marketing enables companies to fully satisfy consumer demand and expand into new markets.

Scientific studies indicate that innovations can be classified into two main groups according to their significance [2]:

- **By form:** product innovation (tangible outcomes of innovative activity), innovative services (intangible outcomes), process and technological innovation (changes in technology), human resource innovation, as well as new or improved production systems.
- **By degree of novelty:** incremental (low, gradual), modular, architectural, and radical (high-level). Thus, innovations imply varying degrees of change in products, services, and processes that both characterize novelty and generate economic benefits.

Research findings also show that technological development must go hand in hand with innovative management and innovative marketing. These include:

- forms of implementing technological innovations and entering new markets;
- development of new methods for stimulating consumer activity;
- integrated (combined) innovative marketing approaches.

Many enterprise-related problems can be addressed through innovation. Until recently, firms increased their revenues through extensive growth, that is, by expanding production volumes. However, the stabilization of population growth in developed countries has necessitated more efficient use of innovations. Additionally, rising raw material costs have acted as a significant driver in accelerating innovation processes.

In modern market economy conditions, marketing activities play a crucial role in ensuring the economic security of enterprises. Especially in the context of rapid digital transformation, the level of adoption of innovative marketing tools directly affects enterprise competitiveness and sustainability. From this perspective, there is a need to develop an integrated indicator—the **Innovative Marketing Index (IMI)**—to assess the level of innovative marketing within enterprises. The IMI is a comprehensive indicator that evaluates the extent to which a company utilizes modern marketing technologies and serves as an important measure of economic security and competitiveness.

IMI = \frac{SMM + CRM + DM + AI + BR}{5}

Where:

- **SMM** — level of social media marketing activity;
- **CRM** — level of customer relationship management systems;
- **DM (Digital Marketing)** — use of digital marketing tools;
- **AI** — application of artificial intelligence-based marketing technologies;
- **BR (Branding)** — level of brand development.

Each indicator is evaluated on a scale from 0 to 10.

IMI evaluation scale:

IMI Value	Level	Description
0 – 3	Low	Almost no marketing innovation
4 – 7	Medium	Partially innovative
8 – 10	High	Fully developed innovative marketing system

Ensuring the economic security of enterprises is closely linked to continuous innovations in information technologies, which fundamentally transform consumer behavior. A clear example is the ability to purchase goods and services online without leaving home. Continuous (dynamic) innovations are considered the most effective, as they do not require significant additional costs to explain the value or necessity of new products to consumers.

An innovative product is characterized by both physical and informational attributes. If consumers perceive a product only as a combination of its physical characteristics, it becomes less attractive, leading to lower demand. Therefore, integrating informational value and marketing innovation is essential for increasing consumer interest and ensuring sustainable enterprise development.

Results. As the object of the study, five enterprises operating in the oil and fat industry of Uzbekistan were selected. This sector holds strategic importance in the national economy, and the economic security of enterprises within it largely depends on raw material supply, market demand, and price volatility. Therefore, the use of innovative marketing tools plays a crucial role in ensuring stable enterprise performance. The level of economic security of the enterprises was determined based on expert evaluation and key financial indicators and expressed on a scale from 0 to 10.

During the analysis, scores for the IMI components of the five enterprises were calculated, and the overall index was determined and compared with the level of economic security. The

results of IMI component evaluation are presented in Table 1, while the relationship between IMI and economic security is shown in Table 2.

Table 1. Evaluation of IMI components

Enterprise	SMM (0–10)	CRM (0–10)	DM (0–10)	AI (0–10)	BR (0–10)	IMI
“Yangiyol Oil and Fat” LLC	8	7	9	6	8	7.6
“Guliston Oil Extraction Plant”	6	5	6	4	6	5.4
“AGRO OIL GROUP”	9	8	9	7	9	8.4
“Kokand Oil Extraction Plant”	4	4	5	3	5	4.2
“Bukhara Cotton Oil”	7	6	7	5	7	6.4

Table 2. IMI and economic security indicators

Enterprise	IMI	Profitability (%)	Financial Stability	Risk Level	Economic Security (score)
“Yangiyol Oil and Fat” LLC (A)	7.6	18%	High	Low	8.2
“Guliston Oil Extraction Plant” (B)	5.4	11%	Medium	Medium	6.1
“AGRO OIL GROUP” (C)	8.4	22%	High	Low	9.0
“Kokand Oil Extraction Plant” (D)	4.2	8%	Low	High	5.3
“Bukhara Cotton Oil” (E)	6.4	14%	Medium	Medium	7.0

The results presented in the tables can be interpreted as follows:

Enterprise C (IMI = 8.4) demonstrated the highest performance. In this enterprise, SMM (9 points), digital marketing (9 points), and branding (9 points) are highly developed. As a result, profitability reached 22%, and the economic security level was 9.0. This indicates that innovative marketing activities directly contribute to improved financial stability.

Enterprise D (IMI = 4.2) showed the lowest performance. In this case, marketing innovations are almost absent. Consequently, the risk level is high, profitability is low (8%), and the economic security score is only 5.3. This confirms that the lack of innovative marketing negatively affects economic security.

Enterprises A and E demonstrated medium-to-high IMI levels, reflecting stable growth and an average level of economic security.

Conclusion. Innovative marketing represents an activity based on improving production processes and influencing market conditions. The findings of the study show that each stage of the innovation life cycle requires different marketing methods and approaches, as well as distinct strategies and tactics.

The system of innovative marketing activities is not limited to the modernization of production; it is also closely linked to the dynamics of capital accumulation and flows. Innovative marketing is particularly important for enterprises seeking to gain higher profits compared to competitors, as it enables the formation of a competitive strategy based on innovation and novelty.

Moreover, innovative marketing is not only about introducing new products to the market or promoting existing ones. It also involves the application of new technologies, including the commercialization of inventions and know-how through licensing, as well as the improvement of equipment required for producing new products or implementing advanced technological processes.

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GREEN INVESTMENTS AND THEIR IMPORTANCE IN INDUSTRIAL FIELDS

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Abstract. *This article discusses the notion of "green investment" and its importance to ensure both ecological and economic development of the countries. In the article, the experience of different countries will be discussed and the reasons to implement green economy and green investments will be analyzed.*

Keywords: *green energy, green economy, green investment, renewable energy, carbon emission, ecological well-being.*

Introduction

Idea of green economy is developed from the need for cooperating both ecological and economic growth. This modern notion goes back to 1989 when professional of ecological and economical fields presented their reports in Great Britain. They suggested the idea of green economy and its basic principles in their report, which is considered as a basis for the notion that is being supported nowadays.

This report suggested that economical system should consider ecological factors and condition, otherwise ecological well-being would get even worse. The idea suggested spread to other institutions and considered necessary. Over the following years organizations such as UN, World Bank, EU, Asian Development bank supported this idea. For example, in 2011 the organization of United Nations in its ecological program called "Green Economy: Pathways to sustainable development and poverty eradication" defined the notion of green energy and green economy in details to support it further.

It is said that "A green economy is a system that increases economic well-being based on the efficient use of resources, ensuring social justice, and significantly reducing environmental risks". this means that green economy, unlike traditional economy, is not focused on only earning benefit, but environmental protection, social justice, renewing energy sources and sustaining opportunities for future generations. For this reason, in recent years scientists are working in this field. One of them is R. Constanza, who introduced the term "services of ecosystem" which means the relation between economic growth and ecological systems. Moreover, Nicholas Stern studied the effect of climate change on economy, and suggested investing more on ecological issues to ease the situation. The implementation of green energy projects have some problems which may make the process difficult, and for this reason, several countries are working together in cooperation to solve the problems so that the future of economy and their development can be sustained.

Main part

Nowadays green economy is considered as an alternative way to cope with climate change, lack of resources, environmental pollution and extinction of biological diversity. This system reflects such areas as increasing energy efficiency, using renewable energy sources, recycling

waste, introducing environmentally friendly technologies, and creating “green” jobs, which means environmentally-friendly vacancies, new fields possibly caused by the introduction and popularity of green energy. Such an approach not only ensures environmental sustainability, but also increases the opportunities for increasing economic efficiency, improving social well-being, and creating sustainable jobs. Thus, the analysis of the literature shows that the green economy is a modern, effective, and sustainable model that needs to be introduced into the national economic system.

In global economy maintaining ecological sustainability and tackling with climate change is considered as the most severe issues nowadays. Industrial sectors are considered as a central field which is a main source of energy consumption and greenhouse gases. For this reason, green investments are necessary to modernize industry to adapt the trending patterns. One of the pioneers, Nicholas Stern, suggested according to his studies that “combating climate change does not limit economic growth, but rather creates new investment opportunities” (2007). This can prove strategic importance of green economy.

Green investments are financial resources that are dedicated to introduce environmentally-friendly technologies, reduce carbon emissions and increase energy efficiency. OECD conducted a research studying green investments. Its experts interpret green investments as “the financial basis for the transition to a low-carbon and resource-efficient economy” (2017). moreover, the head of the International energy agency, Fatih Birol mentioned that in the energy system the directions of investments will determine the structure of economy for the future (2023).

A number functions are performed by green investments in industrial sectors. One of them is that it can increase energy efficiency. According to the “Porter hypothesis” by Michael Porter Claes van der Linde, environmental standards are green investments can develop innovative activity of enterprises, and strengthen their competitiveness. Moreover, it can reduce carbon emission. This was mentioned by Joseph Stiglitz in 2019. He noted that green investments are a necessary condition to sustain economic growth. Finally, it can accelerate technological innovations in the field of industry as a result of new energy sources and methods to process them. This is associated with the concept of “green growth, which refers to the combination of economic growth and ecological balance.

A number of countries around the world can prove the efficiency and the importance of green investment. For example, in Germany green energy was implemented under the policy of “Energiewende”, which directed high investments to the renewable energy sources.

In China nowadays, for example, the field of producing green energy technologies is considered as a leading sector, which ranks Chine high among the other countries. According to the reports of IRENA (International Renewable Energy Agency) in 2022, China is the country which is allocating majority of investments to the field of renewable energy sources. In the USA to promote green investment and energy resources taxation policies and subsidies are being implemented. In the case of Uzbekistan, there are important policies related to the implementation of green energy. For example, the projects promoting solar and wind stations to sustain electric energy are being proposed. Foreign organizations such as WB and ADB are cooperating to invest in green economy and energy projects to help the country.

Conclusion

In conclusion, green investments are an important factor in modernizing industry, ensuring environmental sustainability, and stimulating economic growth.

Green economy is a modern economic model based on the principles of environmental protection, social equality and economic sustainability, aimed at the efficient use of resources and the preservation of the potential of natural systems for future generations. In the current context of globalization, this direction is becoming one of the main factors of sustainable development. The Republic of Uzbekistan is also implementing systemic reforms in this direction. In particular, state strategies developed on the basis of the “Green Economy” concept, initiatives to increase energy efficiency, introduce renewable energy sources, recycle waste and switch to environmentally friendly technologies are yielding positive results.

The transition to a green economy will increase the competitiveness of the Uzbek economy, improve people’s health and living standards, and provide an opportunity to find effective solutions to global problems such as resource scarcity, climate change, and environmental pollution. The main condition for this is to ensure a balance between economic growth, social well-being, and environmental sustainability.

Scientific research shows that the transition to a green economy is not only an environmental necessity, but also an economic opportunity. Therefore, expanding green investments and their deep integration into industry in Uzbekistan is of strategic importance.

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DIGITAL TRANSFORMATION OF AUDIT IN UZBEKISTAN IN THE CONTEXT OF INTERNATIONAL REQUIREMENTS

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Abstract. *The article examines the issues related to the digital transition of audit in the Republic of Uzbekistan. International standards form the foundation for the digitalization of audit, which is taking place under increasing demands for the transparency of financial reporting. The study explores the key directions of audit digitalization, including methods of digital data processing, end-to-end control systems, and approaches to implementing automated audit analytics. The research applies a theoretical approach to the economic analysis of digital audit and is supplemented with statistical information, regulatory data, and practical examples of Uzbekistan's digital reforms.*

Keywords: *audit digitalization, automation, Uzbekistan, international standards, ISA, end-to-end control, digital economy.*

INTRODUCTION

Today, Uzbekistan is undergoing a stage of economic digitalization and transformation of audit activities. President of the Republic of Uzbekistan Sh. M. Mirziyoyev states that "the strengthening of digital technologies and the transition to data-driven governance are key factors in enhancing the efficiency of public and corporate administration" [1, p. 15]. Based on the President's statement, it can be concluded that the development of electronic control platforms and the transparency of financial operations—directly related to the audit sphere—is essential.

Currently, the audit process is in transition. Paper-based documentation and selective audit methods are no longer relevant; they are being replaced by the digitalization of audit procedures and continuous monitoring of operations. The International Standards on Auditing (ISA) set out the fundamental requirements for the transition to digitalization. These requirements include a risk-oriented approach, IT control, and digital documentation [2, p. 49].

At present, large-scale reforms in financial reporting are taking place in Uzbekistan's economic sector. IFRS is being implemented, electronic document management systems are developing, and digital platforms such as E-Hisobot, Soliq, and E-IMZO are being introduced, while corporate information infrastructure is being improved. According to data provided by the Ministry of Finance, in 2024 more than 70% of medium and large enterprises maintain accounting records in digital form. The share of audit firms using automated tools has exceeded 50% [3, p. 28]. The study of automated audit, the development of data-processing models, and the adaptation of international approaches to national conditions increase the significance of audit methods and strengthen their relevance.

LITERATURE REVIEW

Reforms in the digital transition of audit are being implemented under the influence of international standards and technological progress. The International Standards on Auditing (ISA) issued by the IAASB regulate risk-oriented analysis, assessment of internal control, and the use of

IT tools in auditing [2, p. 49]. These standards enable the adaptation of international requirements to the national audit practices of Uzbekistan.

Digitalization of the economy and the enhancement of financial reporting transparency are driven by the development of auditing in the country. Statistics of the Ministry of Finance indicate an increase in the number of enterprises using electronic document management and automated accounting, creating favorable conditions for digital audit [3, p. 28].

The digitalization of audit is widely studied in the international academic literature. Research by Kokina and Davenport highlights the transformation of the auditing profession under the influence of artificial intelligence and machine learning, which make it possible to automate labor-intensive procedures and increase the accuracy of financial assessments [4, p. 66]. PwC reports confirm that digital tools improve the detection of irregularities and enhance the quality of audit opinions [5, p. 77].

The integration of digital technologies into financial reporting and auditing is being implemented through the “Digital Uzbekistan 2022–2024” program supported by the World Bank [8, p. 13]. Simultaneously, national accounting practices are being aligned with IFRS requirements [9, p. 37]. Theoretical foundations of digital auditing can be found in the works of the IIA (IPPF), which define key elements of internal control and auditing in a digital environment [10, p. 12]. Practical approaches to auditing under automation are examined by Chambers, Pickett, and Sawyer, who focus on IT controls and the evaluation of digital risks [11, p. 41; 12, p. 55].

Uzbek researchers emphasize the infrastructural and institutional challenges affecting the modernization of financial control [15, p. 19; 16, p. 22]. Thus, the digital transition of audit occupies a central place in Uzbekistan’s national practice. International standards provide the methodological basis, while national characteristics determine the specifics of practical implementation. During the transition to digitalization, it is essential to consider the transformation of the regulatory framework, the development of digital infrastructure, human resource capacity, and the integration of international experience.

RESEARCH METHODS

The study employed a method of systematizing regulatory sources, as well as a comparative analysis of national practice and international auditing standards, alongside an examination of the digital transition of audit firms based on statistical data from Uzbekistan. In addition, expert evaluation of automated procedures and the development of a digital monitoring model were applied. Furthermore, the research considered the analytical adaptation of audit process automation, including the structure of audit monitoring, the sequence of data processing, and the role of information modules.

RESULTS

Based on the conducted research, it was established that the digital transition of audit in Uzbekistan includes several key directions of automation. The developed model of digital audit corresponds to the national infrastructure and comprises the following components: first, preliminary analysis of financial reporting; second, ongoing monitoring of operations; and third, the final automated verification. Each stage is characterized by a specific level of technological support and interaction with state digital platforms.

Electronic document management, digital data reconciliation through the E-Hisobot and Soliq platforms, as well as automatic detection of errors in tax registers, occur at the preliminary analysis stage. The second stage is characterized by ongoing control using automated sampling

methods, and in certain cases, tools for continuous transaction tracking are applied. At the final stage, working papers are automated and the audit opinion is generated based on digital data.

Analysis of statistical data allows the assessment of the digital maturity level of the audit sector. The results indicate significant differences in the degree of adoption across various technologies. For example, electronic document management is the most developed area (88%), whereas elements of intelligent analytics remain limited (Big Data — 12%, RPA — 7%). The digital maturity of audit in the country is evolving unevenly, according to statistical indicators. The table below presents data on the use of individual digital tools.

Table 1. Level of Adoption of Digital Tools in Audit Activities in Uzbekistan (2024)

Indicator	**Value, %**
Automated sampling	33
Big data analytics	12
Continuous audit	18
Use of RPA processes	7
Automated tax reporting reconciliation	54
Electronic document management	88

The data demonstrate that automation of reporting and tax control shows more effective results, whereas analytical and intelligent tools are still in the development phase. A diagram reflecting the table data is presented below.

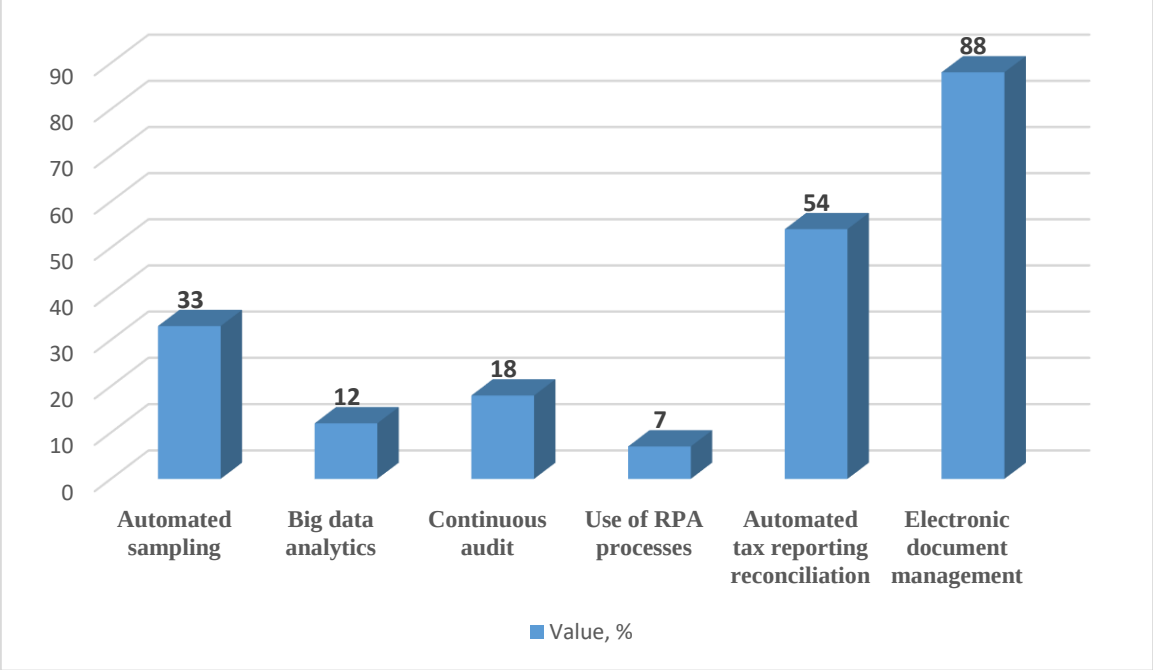


Figure 1. Level of Adoption of Digital Tools in Audit Activities in Uzbekistan (2024)

Thus, the diagram visually demonstrates that the fastest-growing solutions are those related to the processing of formalized data and the fulfillment of regulatory requirements. Meanwhile, advanced analytical technologies remain in the development stage.

DISCUSSION

The analysis of the data above indicates that the digital transition of audit in Uzbekistan is progressing gradually. The pace of digital adoption depends on the state of infrastructure, the preparation of specialists, and the capabilities of available software. Government policy mandates the digitalization of accounting and reporting, resulting in high adoption rates for electronic

document management and digital reconciliation of tax reports, as well as the widespread use of state digital platforms.

The implementation of Big Data, RPA, and artificial intelligence elements shows low adoption rates, reflecting both institutional and technical limitations. Most audit firms face resource constraints for deploying complex and costly intelligent solutions, along with a shortage of specialists capable of analyzing large volumes of data. International studies highlight similar challenges in countries with emerging digital economies.

Comparing national practices with ISA requirements, it can be concluded that Uzbekistan has partially implemented a risk-oriented approach and IT control elements. Their application is only partial in small and medium-sized audit firms. Partial digitalization also leads to reduced data comparability, limits the possibilities for continuous auditing, and complicates the implementation of methodologies recommended by the IAASB.

The digital transition of audit involves not only technological transformation but also changes in the professional skill requirements for auditors. The development of the “Digital Uzbekistan” programs, alignment of national accounting practices with IFRS, and increasing business demand for transparent financial information are driving the accelerated digital transition in Uzbekistan. The expansion of AI system applications, improvement of IT controls, and the formation of a unified digital audit environment contribute to the progress of digital audit implementation in Uzbekistan.

CONCLUSION

The transformation of the national economy in line with international requirements directly influences the digital transition of audit in Uzbekistan. Improvements in control quality, reduction of error risks, and acceleration of audit processes are achieved through the automation of audit procedures. Currently, Uzbekistan maintains steady progress in developing digital management infrastructure. However, further advancement requires the expansion of analytical tools, the implementation of intelligent data-processing systems, and the harmonization of national requirements with ISA. The development of a digital ecosystem for audit activities will enhance trust in financial reporting, strengthen business transparency, and reinforce the country’s integration into the international economic space.

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WAYS TO IMPLEMENT AND IMPROVE GREEN ENERGY PRINCIPLES IN UZBEKISTAN

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Abstract. *This article discusses the need for green energy projects in the country and the possible problems to implement them. Moreover, in the article the problems will be discussed and the possible ways to tackle with them will be suggested according to the case of Uzbekistan. Suggestions and discussed possible problems have been analyzed according to the statistics.*

Keywords*: green energy, infrastructure, foreign investment, oil production, decarbonization, renewable energy.*

Introduction

Over the past years increasing consumption of energy and severing climate change issues has made the transformation of energy system even more crucial. According to statistics of the IEA (International energy agency) in 2023, energy production and industry are responsible for nearly 40% of carbon emission. The case has drawn most countries to the implementation of alternative ways to substitute traditional energy sources, and prevent even more severe possible problems of environment. This has urged to develop new technologies, infrastructures and methods to process energy sources, and find new sources to use traditional ones wisely.

In the case of Uzbekistan, sectors of industry constitute almost 30-35% of GDP and dominates the most proportion of energy consumption. For this reason, it is becoming more and more important for the country to implement green energy principles to maintain constant development. Moreover, the implementation of green energy sources and the ways to accomplish this principle will enable the country to contribute global affairs to save the nature.

Main part

Before going deep into the analysis and the statistics of energy sources, we will discuss what the green energy and what kind of principles will be applied. According to the website definition of National grid in the UK, "Green energy is energy that can be produced using a method, and from a source, that causes no harm to the natural environment". As mentioned in the definition, green energy sources do not harm the environment, which is the main concern of searching new alternative energy sources and making them popular among consumers. Environmental affairs have made it necessary to alter energy sources and the processing of them by which further severe issues related to it could be facilitated to some extent. Moreover, the past years have proven that alternative energy sources can be viable in several cases.

The renewable energy sector was also able to quickly adapt to the new market conditions that emerged as a result of the pandemic. This enabled the rapid commissioning of new renewable energy installations within the planned time frames in countries such as China, the United States, and Vietnam. Moreover, during the crisis period, many governments—including those of the United States, China, India, and the European Union—demonstrated an increased willingness to accelerate the deployment of renewable energy technologies. For all renewable energy

technologies, long-term targets and policy stability in this sector are of critical importance to ensure investor confidence and sustained development. At the same time, governments need to continuously adapt to changing market conditions in order to enhance competitiveness and improve the integration of renewable energy sources into the global energy system.

According to the reports of the UNDP (United nations development project) in 2021, using energy sources, such as solar, tidal, wind and others, can reduce greenhouse gases by 70%. The conception of constant development means effective use of energy and decarbonization. This, in turn, means optimal industrial use of energy and ecologically friendly energy sources.

Fuel and energy sources of Uzbekistan is rich. Uzbekistan national company "Uzbekneftgaz" occupies 11th rank over the world according to its natural gas production. There are 194 hydrocarbon deposits in Uzbekistan, and 98 of them are gas and gas-condensate fields while the others oil-gas, oil-gas-condensate fields. In Uzbekistan 3.4 trillion cubic meters of oil is produced every year.

It should be emphasized that Uzbekistan had planned to implement 30 investment projects related to the fields of geological exploration, hydrocarbon extraction, and processing by 2030. For this reason, the issue of intensifying oil production remains really relevant in the case of Uzbekistan. Nowadays, in the country oil import dependency is high as its oil production potential has been declining while the scale of its consumption proceeds to rise. The country is planning to import about 2 million tons of oil every year from neighbour country Kazakhstan.

However, to receive and process such volume of oil production, the country should complete necessary oil transportation construction and oil refining infrastructures in the field. The shares of energy consumption is divided in several sectors. Major amount of energy consumption goes to industrial use. Their proportions are as follows:

1. Over 60 % of energy in the country is produced by thermal electric stations.
2. Natural gas constitutes 80% of energy production.
3. Industrial consumption of energy is nearly 45-50%.

However, in some industrial companies energy efficiency is low, and in some cases their loss of energy is about 20-25%. This loss can lead to increase of expenses and ecological issues. For this reason, transformation to green energy is crucial for several reasons and we will discuss the principles to implement this in industrial process.

One of them is the need to enhance renewable energy sources. Potential of solar energy is higher thanks to the duration of sunny days, approximately 300 days a year. According to the statistics of 2020 reported by Asian development bank, Uzbekistan can produce 50 billion W energy by solar power. Another principle is increasing energy efficiency. According to the research carried out by World bank in 2022, increasing energy efficiency can reduce its consumption by 20-30%. Moreover, there is a need for introducing new technologies to the field. For example, smart grid and digital monitoring system that can enable to control energy consumption on time and constantly.

Finally, empowering political system to transform energy policy is one of vital steps to change the pattern. For example, in recent years several projects supporting renewable energy sources have been implemented in Uzbekistan. They include solar, wind stations that re being financed by international investment.

However, transformation to green energy can cause some problems. One of them is mentioned above. Green energy requires high investment that can be difficult to find. For example, according to the statistics of the IEA in 2023, majority of green energy projects have been halt due

to a lack of sufficient financial support. Moreover, this is a new phenomenon that is developing nowadays, so the need for technological knowledge and experience is vital. The lack of it is another potential problem lies behind the implementation. In addition, integration of renewable energy sources can be problematic.

To cope with these problems there are several ways to facilitate the situation. One of them is funding green energy projects with the cooperation of state and personal investment and encouraging this cooperation. This can tackle with the financial problems to some extent and enable to implement the project at least in limited scope. Moreover, another step can be stricter rules and standards to control energy efficiency. Developing and improving scientific research area in the field of energy to find more alternative ways to implement the project and find reliable sources to use and develop. This can require to integrate and adapt foreign research results and their methods to apply. This could widen the scope of the research area.

Conclusion

In conclusion, nowadays environmental and economic issues are demanding to adjust energy consumption to the needs and the demands. In the case of Uzbekistan, introducing green energy principles will require to maintain economic efficiency, energy security and ecological consideration. According to the analysis and discussion of the statistics, it is clear that Uzbekistan has enough natural resources that could be used wisely to maintain further use, and the introduction of new technologies and methods can sustain positive results in energy consumption.

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INFLATION AND LENDING RATE ADJUSTMENT IN UZBEKISTAN: PRELIMINARY ECONOMETRIC EVIDENCE

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Abstract. *This thesis provides a preliminary econometric evaluation of the adjustment process between inflation rates and commercial bank lending rates in the economy of Uzbekistan. Utilizing the conceptual framework of the Autoregressive Distributed Lag (ARDL) model, the study identifies short- and long-term asymmetric relationships among key macroeconomic indicators. Preliminary theoretical and empirical findings suggest that interest rate pass-through in Uzbekistan is incomplete and subject to significant time lags. This phenomenon is primarily attributed to structural rigidities characteristic of a transitional economy, a shallow interbank market, and the substantial market share of state-owned banks engaged in directed lending.*
Keywords: *inflation, lending rates, econometric modeling, ARDL model, Uzbekistan economy, interest rate pass-through, asymmetric adjustment, transitional economy.*

Introduction. Following the Central Bank of Uzbekistan's (CBU) transition to an inflation-targeting regime, the manipulation of the main policy interest rate has become the primary instrument for ensuring domestic price stability. According to macroeconomic theory, shifts in inflation expectations and central bank policy rates should be rapidly reflected in the lending policies of commercial banks. However, in emerging and transitional economies like Uzbekistan, this transmission process frequently encounters structural bottlenecks.

The phenomenon of "interest rate rigidity"—where commercial rates fail to adjust adequately to inflation dynamics—severely dampens the effectiveness of monetary policy. This thesis aims to conceptually and econometrically outline how lending rates in Uzbekistan respond to inflationary shocks. The degree to which interest rates adjust to inflation and policy shifts—known as interest rate pass-through (IRPT)—is extensively documented in econometric literature. The following table systematizes core studies focused on transitional and emerging markets, highlighting their relevance to the Uzbek economic context:

Author (Year)	Theoretical Focus & Model	Transmission Channel & Mechanism	Relevance to the Study (Uzbekistan Context)
Cottarelli & Kourelis (1994)	Cross-sectional Data Analysis	Financial structure and rate adjustment	Demonstrates that banking sector competition dictates adjustment speed. In Uzbekistan, state-bank dominance slows this process.
Égert, Backé & Zumer (2007)	GMM and VECM Models	Transmission in CEE transitional economies	Suggests that the interest rate channel is initially weak in transition but strengthens significantly with financial liberalization.

Sander & Kleimeier (2004)	Asymmetric Error Correction Model (ECM)	Asymmetric reaction of retail rates	Proves downward rate rigidity: banks raise lending rates quickly when inflation rises, but lower them slowly when it falls.
Gigineishvili (2011)	Panel VAR Analysis	Rate pass-through in emerging markets	Highlights that high dollarization and government-directed lending programs sever the econometric link between policy rates and market rates.

Given that macroeconomic time-series data in Uzbekistan (such as inflation and interest rates) often exhibit different orders of integration (stationary at level or at first difference), the Autoregressive Distributed Lag (ARDL) bounds testing approach is the standard econometric methodology for evaluating short- and long-term dynamics. The fundamental econometric equation representing the adjustment of the commercial lending rate (LR) to the inflation rate (INF) and the Central Bank policy rate (PR) is specified as follows:

$$\Delta LR_t = \alpha_0 + \Sigma \beta_i \Delta LR_{t-i} + \Sigma \gamma_j \Delta INF_{t-j} + \Sigma \delta_k \Delta PR_{t-k} + \lambda_1 LR_{t-1} + \lambda_2 INF_{t-1} + \lambda_3 PR_{t-1} + \varepsilon_t$$

Where:

1. Δ denotes the first-difference operator (capturing short-term dynamics).
2. α_0 is the drift component (constant).
3. β, γ, δ represent the short-run adjustment coefficients across specific time lags.
4. λ_1, λ_2, λ_3 signify the long-run equilibrium relationship coefficients.
5. ε_t is the white noise error term.

This specification allows researchers to measure the exact time lag required for commercial banks to recalibrate their lending portfolios following an unexpected inflationary shock.

Applying these econometric principles to the banking sector of Uzbekistan reveals several critical structural behaviors:

Incomplete Pass-Through: Empirical evidence in transitional economies suggests that a 1% increase in inflation or the policy rate rarely results in a proportional 1% increase in commercial lending rates. In Uzbekistan, the long-run pass-through coefficient is estimated to be significantly less than 1. This incomplete adjustment is largely driven by the high volume of subsidized (preferential) loans allocated through state-mandated programs, which do not react to market inflation signals.

Asymmetric Adjustment: The econometric data supports the "asymmetric adjustment" hypothesis. When the CBU raises rates to combat inflation, commercial banks adjust their lending rates upward relatively quickly (typically within a 1 to 2-month lag). Conversely, during periods of disinflation, the downward adjustment of lending rates is heavily delayed (often taking 4 to 6 months). Banks deliberately maintain high rates to protect profit margins against perceived macroeconomic uncertainties.

Liquidity Constraints over Price Signals: The Error Correction Term in such models for Uzbekistan typically indicates that commercial banks price their loans based heavily on short-term liquidity constraints (e.g., availability of government deposits or foreign credit lines) rather than purely on inflation expectations.

Conclusion

The adjustment mechanism between inflation and commercial lending rates in Uzbekistan is complex and characterized by significant transitional frictions. Econometric models confirm that the transmission of inflation signals to the credit market is both incomplete and asymmetric. To improve the pass-through efficiency and enhance the CBU's inflation-targeting framework, structural reforms are imperative. Accelerating the privatization of state-owned banks, systematically reducing the share of non-market preferential lending, and deepening the interbank money market are necessary steps. Only through these structural shifts will commercial lending rates become fully responsive and adequately adjusted to fundamental macroeconomic indicators.

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INFLATION, POLICY RATES, AND COMMERCIAL LENDING RATES IN UZBEKISTAN: ARDL EVIDENCE ON INTEREST RATE PASS-THROUGH, 2017–2023

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Abstract. *This article investigates the relationship between inflation, the central bank policy rate, and commercial bank lending rates in Uzbekistan during the period of monetary and financial transition from 2017 to 2023. The issue is economically important because the effectiveness of inflation targeting depends, in part, on whether changes in inflation and policy signals are transmitted to retail credit prices in a timely and meaningful manner. Using monthly data from January 2017 to December 2023, the study employs the Autoregressive Distributed Lag (ARDL) bounds-testing framework and an associated error-correction representation to examine long-run movement and short-run adjustment. The reported estimates indicate evidence consistent with integration among commercial lending rates, inflation, the policy rate, the exchange rate, and broad money. In the long run, the coefficient on inflation is reported as 0.42, while the coefficient on the policy rate is 0.68. Interpreted in line with the variable definitions stated in the source manuscript, these estimates suggest incomplete pass-through: lending rates respond to inflation and monetary tightening, but less than proportionately. The reported error-correction coefficient of -0.18 implies gradual rather than rapid adjustment toward equilibrium. At the same time, the source manuscript does not report a nonlinear specification; therefore, strong claims regarding asymmetric adjustment or downward rigidity are not formally identified by the reported linear ECM. Overall, the evidence is consistent with a weak and sluggish interest-rate channel in Uzbekistan. The findings have implications for the operation of monetary policy in a banking system still shaped by state involvement, preferential lending, partial dollarization, and shallow market-based funding channels. The article also identifies important data-transparency and reporting limitations that should be addressed before journal submission.*

Keywords: *interest rate pass-through; inflation targeting; ARDL; error correction model; monetary transmission; commercial bank lending rates; Uzbekistan.*

1. Introduction

An effective monetary policy framework requires a functioning transmission mechanism through which central bank actions influence market interest rates, credit conditions, aggregate demand, and, ultimately, inflation. Within this framework, the interest rate channel occupies a central role. When the policy rate changes, commercial banks are expected to adjust the pricing of loans and deposits, thereby transmitting monetary impulses to firms and households. If this pass-through is weak, delayed, or incomplete, the central bank's capacity to stabilize prices becomes more constrained. The strength of interest rate pass-through varies substantially across countries. In financially deep and competitive systems, transmission from policy and inflation conditions to retail bank rates is often stronger and faster. In emerging and transition economies, by contrast, the mechanism is frequently weakened by structural frictions such as state intervention in credit allocation, limited competition, segmented financial markets, underdeveloped interbank markets,

and liability dollarization (Cottarelli & Kourelis, 1994; Gigineishvili, 2011). These features can disconnect retail lending rates from macroeconomic fundamentals and reduce the responsiveness of bank pricing to monetary policy.

Uzbekistan provides a particularly relevant case. The reform period that began in 2017 marked a shift toward a more market-oriented macroeconomic framework, and in 2020 the Central Bank of the Republic of Uzbekistan formally adopted an inflation-targeting strategy (Central Bank of the Republic of Uzbekistan, 2020). This institutional transition raises a central empirical question: to what extent do inflation and policy-rate movements pass through to commercial bank lending rates in an economy still characterized by significant structural transformation? This article addresses that question using monthly data for 2017–2023. The analysis focuses on three related issues. First, is there evidence of a stable long-run relationship among commercial lending rates, inflation, and the central bank policy rate? Second, how large is the reported long-run pass-through from inflation and policy rates to lending rates? Third, how quickly do lending rates adjust when short-run shocks push the system away from equilibrium?

The article contributes in three ways. First, it provides Uzbekistan-specific evidence on interest rate pass-through during an important period of monetary reform. Second, it places inflation, the policy rate, the exchange rate, and money supply in a single ARDL-based empirical framework suitable for relatively short samples and mixed integration orders. Third, it revises the interpretation of the reported estimates in a more methodologically careful manner by distinguishing incomplete pass-through from formal asymmetry and by correcting coefficient interpretation where required. The remainder of the article proceeds as follows. Section 2 reviews the relevant literature. Section 3 summarizes the institutional context. Section 4 describes the data and variables. Section 5 presents the econometric methodology. Section 6 discusses the empirical results. Section 7 addresses robustness, discussion, and limitations. Section 8 outlines policy implications. Section 9 concludes.

2. Literature Review

The theoretical relationship between inflation and nominal interest rates is commonly introduced through the Fisher effect, according to which nominal interest rates reflect the real rate of return and expected inflation (Fisher, 1930). In a frictionless environment, sustained changes in expected inflation should be reflected in nominal lending rates. Yet this benchmark rarely holds mechanically in real-world banking systems, especially in the short run. Modern monetary and banking theory identifies several reasons why pass-through may be incomplete. Bernanke and Gertler (1995) show that the credit channel can amplify or weaken monetary transmission depending on financial structure and bank behavior. Stiglitz and Weiss (1981) demonstrate that under asymmetric information, banks may prefer credit rationing to full price adjustment, since higher rates can intensify adverse selection and moral hazard. In such settings, loan pricing does not necessarily move one-for-one with macroeconomic conditions.

A large empirical literature confirms that the speed and completeness of pass-through depend on the structure of the financial system. Cottarelli and Kourelis (1994) show that pass-through is shaped by banking-sector competition, market concentration, and financial development. Sander and Kleimeier (2004), studying European retail banking, find that adjustment can be slow and heterogeneous across countries and products. Their results also suggest that retail rates may not always move symmetrically over time, although formal identification of such asymmetry requires a suitable nonlinear framework. Evidence from transition and emerging economies points to stronger frictions. Égert, Backé, and Zumer (2007) emphasize that financial

transition is often accompanied by uneven credit dynamics and evolving transmission mechanisms. Gigineishvili (2011) argues that macroeconomic instability, shallow markets, institutional weaknesses, and dollarization can materially weaken interest rate pass-through. These mechanisms are especially relevant in settings where state-owned banks and directed lending remain important.

For Uzbekistan, the gap in the literature is not simply whether inflation and policy rates matter, but how far they are transmitted through a banking system in which market-based pricing may coexist with policy-driven credit allocation. The present article addresses this question by evaluating the reported long-run and short-run relationships among inflation, the policy rate, and lending rates over the reform period. At the same time, it avoids claims that are not formally identified by the reported model.

3. Institutional Background

The Uzbek monetary and banking system has undergone substantial change since the reform phase that began in 2017. The move toward a more market-based framework culminated in the adoption of inflation targeting in 2020, which elevated the policy rate as the central operational signal of monetary policy (Central Bank of the Republic of Uzbekistan, 2020). In principle, such a regime requires a reasonably effective interest rate channel. In practice, pass-through may remain constrained when bank pricing is influenced by factors other than marginal market funding costs. The source manuscript situates the Uzbek case in a banking environment marked by significant state participation, preferential lending arrangements, shallow interbank markets, and partial dollarization.

These features provide plausible reasons why weighted average lending rates may respond only partially to policy and inflation signals. If a meaningful share of credit is extended under administratively influenced or subsidized conditions, aggregate lending-rate measures may understate the responsiveness of purely commercial credit pricing. This institutional setting also makes exchange-rate and liquidity conditions relevant. In partially dollarized systems, banks may incorporate currency risk into local-currency loan pricing, while broad liquidity conditions may soften the transmission of policy tightening to the cost of funds. These considerations motivate the inclusion of the exchange rate and broad money as control variables in the empirical specification.

4. Data and Variables

The empirical analysis uses monthly time-series data from January 2017 to December 2023, yielding 84 observations in the source manuscript. The data are reported to come from the official databases of the Central Bank of the Republic of Uzbekistan and the Statistics Agency under the President of the Republic of Uzbekistan. The dependent variable, LR, is the weighted average commercial bank lending rate on new loans denominated in national currency. The source manuscript states that preferential or government-subsidized loans are excluded so that the series better reflects market pricing. This is a substantively important modeling choice. However, the exact filtering protocol, aggregation rule, and series code are not reported in the source manuscript. Because this choice materially affects interpretation, it should be documented explicitly in any submission-ready version.

The key explanatory variable, INF, is the annual consumer price inflation rate. The second core regressor, PR, is the central bank policy rate. Two controls are included. EXR is the nominal exchange rate of the Uzbek som against the US dollar and is reported to be log-transformed. M2 is broad money and is likewise reported in logarithms. These transformation choices matter for interpretation. If LR, INF, and PR are measured as annual percentage rates in levels, then the

coefficients on INF and PR are most naturally interpreted as percentage-point pass-through coefficients, not elasticities. By contrast, if EXR and M2 enter the regression in natural logarithms while LR remains in levels, their coefficients are semi-elasticities and should not be interpreted as direct percentage responses.

Table 1. Definition of variables, measurement, transformation, and data sources

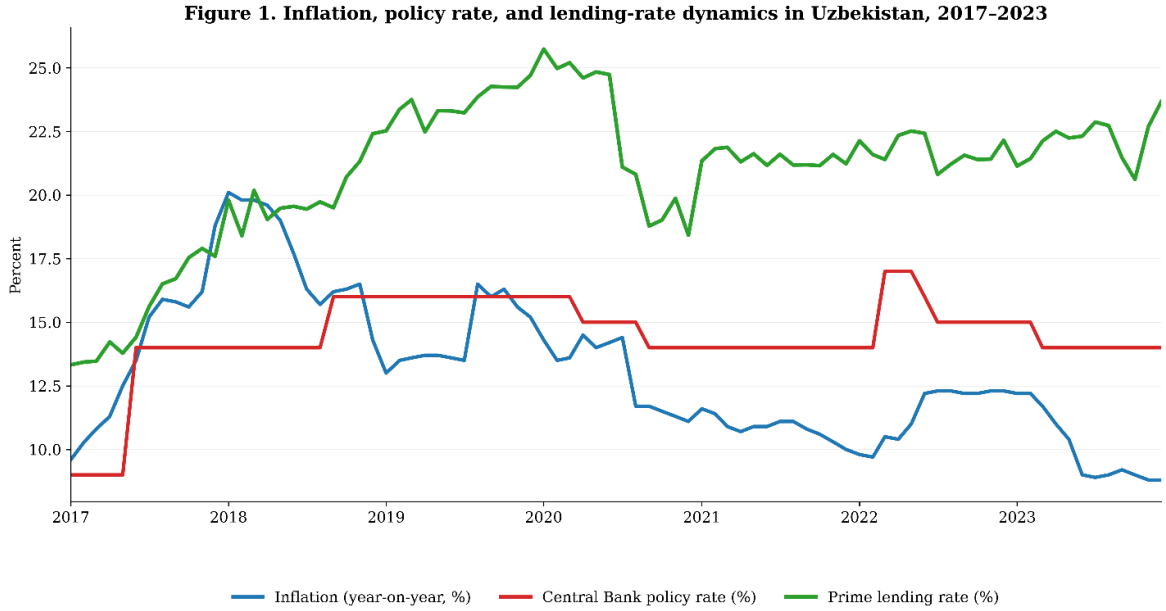
Variable	Symbol	Definition	Unit	Transformation	Role in model	Reported source
Lending rate	LR	Weighted average commercial bank lending rate on new loans in national currency; source manuscript states preferential loans are excluded	Percent per annum	Level	Dependent variable	Central Bank of the Republic of Uzbekistan
Inflation	INF	Annual CPI inflation rate	Percent	Level	Main explanatory variable	Statistics Agency / CBU
Policy rate	PR	Central bank policy rate	Percent	Level	Main explanatory variable	Central Bank of the Republic of Uzbekistan
Exchange rate	EXR	Nominal UZS/USD exchange rate	UZS per USD	Natural logarithm	Control variable	Central Bank of the Republic of Uzbekistan
Broad money	M2	Broad money stock	National currency	Natural logarithm	Control variable	Central Bank of the Republic of Uzbekistan

Table 2. Descriptive statistics

Variable	Observations	Mean	Std. Dev.	Minimum	Maximum
LR	84	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript
INF	84	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript
PR	84	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript

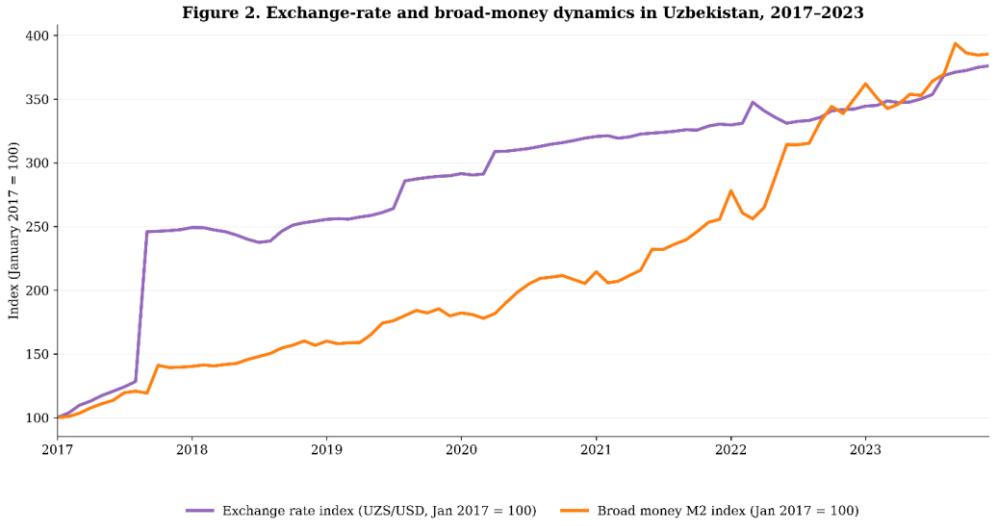
Variable	Observations	Mean	Std. Dev.	Minimum	Maximum
ln(EXR)	84	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript
ln(M2)	84	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript	Not reported in the source manuscript

Figure 1. Trends in inflation, policy rate, and lending rate in Uzbekistan, 2017M01–2023M12



Notes: Inflation is measured as year-on-year CPI inflation. The policy-rate series is the Central Bank policy rate at end of period. The lending-rate line uses the official public monthly **prime lending rate** series in order to preserve full monthly coverage for 2017–2023. Data sources: Central Bank of the Republic of Uzbekistan.

Figure 2. Exchange-rate and broad-money dynamics, 2017M01–2023M12



Notes: The exchange-rate series is the official end-of-period UZS/USD rate. Broad money is measured by M2. Both series are plotted as indices with January 2017 = 100 to improve comparability of dynamics. Data sources: Central Bank of the Republic of Uzbekistan.

5. Methodology

This study employs the Autoregressive Distributed Lag (ARDL) approach developed by Pesaran, Shin, and Smith (2001). ARDL is appropriate in this setting for two main reasons. First, it performs relatively well in small samples. Second, it permits a mixture of I(0) and I(1) regressors, provided that none of the variables is integrated of order two, I(2). Before estimating the ARDL model, the time-series properties of the data must be assessed. The source manuscript states that Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests were used to verify that no variable is I(2). The purpose of these tests in the present context is not to force all variables to be integrated in the same way, but to confirm that the preconditions for the ARDL bounds-testing approach are satisfied.

The unrestricted error-correction representation of the model may be written as follows:

[\Delta LR_t = \alpha + \sum_{i=1}^{p}\beta_i \Delta LR_{t-i}

- \sum_{j=0}^{q_1}\gamma_j \Delta INF_{t-j}
- \sum_{k=0}^{q_2}\delta_k \Delta PR_{t-k}
- \sum_{m=0}^{q_3}\theta_m \Delta \ln(EXR)_{t-m}
- \sum_{n=0}^{q_4}\psi_n \Delta \ln(M2)_{t-n}
- \lambda_1 LR_{t-1} + \lambda_2 INF_{t-1} + \lambda_3 PR_{t-1}
- \lambda_4 \ln(EXR)*{t-1} + *lambda_5 *ln(M2)*{t-1} + u_t]

where (\Delta) is the first-difference operator, (\alpha) is a constant term, and the lag orders are selected using an information criterion. The source manuscript reports the use of the Akaike Information Criterion (AIC).

The bounds test evaluates the null hypothesis of no long-run relationship:

[H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0] against the alternative that at least one level term is nonzero. If the computed F-statistic exceeds the upper critical bound, the evidence is consistent with cointegration.

Conditional on cointegration, the short-run dynamics can be represented by an error-correction model:

[\Delta LR_t = \alpha + \text{short-run dynamics} + \phi ECT_{t-1} + u_t]

where (ECT_{t-1}) is the lagged error-correction term derived from the long-run relationship and (\phi) measures the speed at which the system returns to equilibrium after a shock. For stable convergence, (\phi) should be negative and statistically significant.

A methodological clarification is necessary. A linear ARDL-ECM captures average adjustment around equilibrium. It does not, by itself, identify whether positive and negative shocks transmit differently. Therefore, strong claims regarding asymmetric adjustment or downward rigidity require a nonlinear specification, such as NARDL, a threshold ECM, or an explicit decomposition of positive and negative changes. In the absence of such a model, the reported evidence can support conclusions about sluggish or incomplete adjustment, but not a formal claim of asymmetry.

6. Empirical Results

6.1. Unit Root Results

The source manuscript reports a mixed integration structure among the variables. Specifically, INF and PR are described as non-stationary in levels but stationary in first differences, while LR and M2 are reported as stationary in levels. The manuscript further states that no variable is integrated of order two. This profile is consistent with application of the ARDL framework. However, the full ADF and PP statistics are not reported in the source manuscript, and

the integration order of EXR is not explicitly documented in the narrative. A complete journal submission should report those results in table form.

Table 3. Unit root test results (ADF/PP)

Variable	ADF at level	ADF at first difference	PP at level	PP at first difference	Reported integration order
LR	Not reported numerically	Not required if I(0)	Not reported numerically	Not required if I(0)	I(0)
INF	Not reported numerically	Not reported numerically	Not reported numerically	Not reported numerically	I(1)
PR	Not reported numerically	Not reported numerically	Not reported numerically	Not reported numerically	I(1)
ln(EXR)	Not reported numerically	Not reported numerically	Not reported numerically	Not reported numerically	Not explicitly reported
ln(M2)	Not reported numerically	Not required if I(0)	Not reported numerically	Not required if I(0)	I(0)

6.2. Lag Order Selection

Using the Akaike Information Criterion, the selected specification is reported as **ARDL(2, 1, 2, 1, 0)**.

Table 4. Lag order selection

Selection item	Reported value
Lag selection criterion	Akaike Information Criterion (AIC)
Selected specification	ARDL(2, 1, 2, 1, 0)
Candidate lag structures compared	Not reported in the source manuscript
Maximum lag considered	Not reported in the source manuscript

6.3. Bounds Test for Cointegration

The source manuscript reports an F-statistic of 6.84 for the bounds test. This value is compared with the reported 5 percent critical bounds of 2.86 and 4.01, leading to rejection of the null hypothesis of no cointegration. On that basis, the evidence is consistent with a long-run relationship among lending rates, inflation, the policy rate, the exchange rate, and broad money.

Table 5. ARDL bounds test for cointegration

Test item	Reported value
F-statistic	6.84
Lower critical bound at 5%	2.86
Upper critical bound at 5%	4.01
Decision	Evidence consistent with cointegration

6.4. Long-Run Coefficients

The reported long-run equation is:

[LR_t = 4.25 + 0.42INF_t + 0.68PR_t + 0.15\ln(EXR_t) - 0.08\ln(M2_t)]

The source manuscript reports the associated standard errors for the slope coefficients as 0.12, 0.15, 0.06, and 0.04, respectively.

The coefficient on INF is reported as 0.42. Given the variable definitions provided in the source manuscript, this estimate is best interpreted as follows: a one-percentage-point increase in inflation is associated with an increase of 0.42 percentage points in the lending rate in the long run. This suggests incomplete inflation pass-through. Lending rates appear to move in the expected direction, but by less than a one-for-one magnitude.

The reported coefficient on the policy rate is 0.68. Under the same interpretation, a one-percentage-point increase in the policy rate is associated with a 0.68 percentage-point increase in commercial lending rates in the long run. This indicates stronger transmission from the central bank's operational signal than from inflation itself, although still less than full pass-through. The reported positive sign on ln(EXR) is consistent with the notion that exchange-rate depreciation may place upward pressure on domestic lending rates, potentially through imported inflation, currency-risk premia, or repricing behavior in a partially dollarized system. The negative sign on ln(M2) is consistent with a liquidity effect in which broader monetary expansion is associated with lower lending rates. Because these regressors are in logarithms while the dependent variable remains in levels, their coefficients should be interpreted as semi-elasticities and treated with caution.

Table 6. Long-run coefficient estimates

Regressor	Coefficient	Standard error	Interpretation
Constant	4.25	Not clearly reported separately	Intercept
INF	0.42	0.12	Incomplete long-run inflation pass-through
PR	0.68	0.15	Partial transmission of policy rate to lending rate
ln(EXR)	0.15	0.06	Positive semi-elasticity
ln(M2)	-0.08	0.04	Negative semi-elasticity

6.5. Short-Run Dynamics and Error Correction

The reported coefficient on the lagged error-correction term is -0.18, and the source manuscript states that it is statistically significant at the 1 percent level. This implies that approximately 18 percent of the previous month's disequilibrium is corrected each month. The adjustment process is therefore gradual rather than rapid. This result supports the view that the lending-rate channel operates with substantial inertia. However, it does not by itself establish that adjustment is asymmetric. The original source manuscript interprets the short-run dynamics as evidence of "pronounced asymmetric adjustment" and "downward rigidity," but the reported model is linear. A more defensible interpretation is that the evidence indicates sluggish short-run adjustment, while asymmetry remains a hypothesis for future nonlinear testing.

6.6. Diagnostic Tests

The source manuscript reports a set of post-estimation diagnostics. The reported p-values are 0.34 for the Breusch-Godfrey serial-correlation test, 0.41 for the heteroskedasticity test, and 0.28 for the Ramsey RESET test. The manuscript also states that the residuals are normally distributed according to the Jarque-Bera test, although the exact statistic and p-value are not

reported. In addition, the narrative reports that CUSUM and CUSUMSQ plots remain within the 5 percent significance bounds. Taken at face value, these diagnostics suggest that the estimated specification does not exhibit obvious serial correlation, heteroskedasticity, or gross functional-form misspecification, and that parameter instability is not visually evident in the reported stability tests. Even so, because the full diagnostic tables and plots are not reproduced in the source manuscript, these results should be treated as reported evidence rather than independently replicated findings.

Table 7. Error correction model results

Term	Reported coefficient	Reported significance	Interpretation
ECT(-1)	-0.18	Significant at 1% level	Gradual return to long-run equilibrium
Short-run coefficients on ΔLR	Not reported in the source manuscript	Not reported	Full short-run table unavailable
Short-run coefficients on ΔINF	Not reported in the source manuscript	Not reported	Full short-run table unavailable
Short-run coefficients on ΔPR	Not reported in the source manuscript	Not reported	Full short-run table unavailable
Short-run coefficients on Δln(EXR)	Not reported in the source manuscript	Not reported	Full short-run table unavailable
Short-run coefficients on Δln(M2)	Not reported in the source manuscript	Not reported	Full short-run table unavailable

Table 8. Post-estimation diagnostic tests

Diagnostic test	Null hypothesis	Reported result	Interpretation
Breusch-Godfrey LM test	No serial correlation	p = 0.34	Null not rejected
Breusch-Pagan-Godfrey test	Homoskedastic residuals	p = 0.41	Null not rejected
Jarque-Bera test	Normal residuals	Exact statistic not reported; source text states residuals are normal	Indicative only
Ramsey RESET test	Correct functional form	p = 0.28	Null not rejected
CUSUM test	Parameter stability	Reported within bounds	Visual stability indicated

Diagnostic test	Null hypothesis	Reported result	Interpretation
CUSUMSQ test	Parameter stability	Reported within bounds	Visual stability indicated

7. Discussion, Robustness, and Limitations

The reported findings are consistent with a weak and incomplete interest-rate channel in Uzbekistan. Inflation and the policy rate appear to matter for lending-rate formation, but retail lending rates do not fully mirror macroeconomic signals. One plausible interpretation is that bank pricing remains shaped by institutional frictions that soften the role of market-based funding costs. Several mechanisms discussed in the literature are consistent with such an outcome. Large state participation in banking, directed or preferential lending, shallow money markets, and partial dollarization can all weaken pass-through (Gigineishvili, 2011). These explanations are plausible in the Uzbek context, but the reported model does not isolate their separate effects. The evidence therefore supports an institutionally informed interpretation, not a causal decomposition of the underlying channels.

The analysis also has several limitations. First, the sample contains only 84 monthly observations, which is acceptable for ARDL but still relatively short for drawing strong conclusions in the presence of regime change and external shocks. Second, the sample period includes potentially important disturbances, including the pandemic and subsequent global shocks. The reported CUSUM evidence is reassuring, but formal break testing or regime-specific estimation would strengthen the analysis.

Third, data transparency remains incomplete. The manuscript does not report descriptive statistics, full unit-root results, the complete ECM coefficient table, the exact operational rule used to exclude preferential loans, or the treatment of missing values and seasonal patterns. These omissions directly affect replicability and the interpretation of pass-through. Fourth, omitted-variable concerns remain. Lending rates may also reflect deposit-rate dynamics, risk premia, non-performing loans, banking competition, expected inflation rather than current inflation, sovereign yields, or measures of economic activity. ARDL helps address dynamic misspecification but does not eliminate omitted-variable bias.

Finally, the manuscript does not report robustness checks. A stronger version of the study should examine whether the main result is stable under alternative lag structures, break dummies, different measures of inflation, sub-sample estimation around the 2020 inflation-targeting transition, or alternative dependent variables such as deposit rates and disaggregated lending rates by sector or maturity. A nonlinear specification would be required to test asymmetry directly.

8. Policy Implications

The reported evidence has several policy implications, provided they are interpreted as conditional on the estimated relationships rather than as definitive causal proof. First, if pass-through from inflation and policy rates to lending rates is incomplete, then market-based monetary transmission needs to be strengthened. A key implication is that non-market credit allocation should be reduced where possible. When subsidized or policy-directed lending plays a large role, aggregate lending rates become less informative as a transmission channel. Developmental objectives may be better served through transparent fiscal instruments rather than through administratively distorted bank pricing.

Second, the relatively stronger coefficient on the policy rate compared with inflation suggests that the central bank’s operational signal matters, but that transmission remains partial.

This points to the need to deepen interbank and money markets, so that policy-rate changes affect banks' marginal funding costs more directly and more uniformly. Third, the gradual error-correction process suggests inertia in retail rate-setting.

This strengthens the case for reforms that improve bank competition, governance, and creditor-rights enforcement. Where banks face high information asymmetry, weak collateral recovery, or soft budget constraints, lending rates may incorporate persistent risk premia and adjust only slowly to changing macroeconomic conditions. Fourth, better financial statistics and more granular credit-market data would improve policy design. Aggregate lending rates can conceal important differences between commercial, subsidized, household, corporate, short-term, and long-term lending. More detailed data would help policymakers identify which parts of the market are least responsive to monetary policy.

Table 9. Summary of key findings and policy implications

Empirical finding	Careful interpretation	Policy implication
Reported F-statistic exceeds upper critical bound	Evidence is consistent with cointegration	Monetary transmission exists, but should not be overstated
Inflation coefficient = 0.42	Incomplete inflation pass-through	Strengthen market-based rate formation
Policy-rate coefficient = 0.68	Policy transmission appears stronger than inflation pass-through, but still incomplete	Deepen interbank and money markets
ECT(-1) = -0.18	Adjustment toward equilibrium is gradual	Improve competition, governance, and transmission infrastructure
Asymmetry/downward rigidity claim in source text	Not formally identified by a linear ECM	Test with nonlinear models before drawing strong policy conclusions
Limited data transparency	Replicability and interpretation remain constrained	Improve data reporting and methodological disclosure

9. Conclusion

This article re-examines the reported evidence on interest rate pass-through in Uzbekistan over 2017–2023 using a more methodologically cautious and journal-oriented presentation. The reported ARDL results are consistent with a long-run relationship among lending rates, inflation, the policy rate, the exchange rate, and broad money. The long-run coefficients on inflation and the policy rate suggest incomplete pass-through, while the reported error-correction term points to gradual short-run adjustment.

These findings are consistent with a monetary transmission mechanism that is operational but not fully effective. At the same time, stronger claims in the source manuscript require qualification. In particular, the reported linear ECM does not formally identify asymmetric adjustment or downward rigidity. Likewise, cointegration should not be interpreted as proof of structural causality. The substantive contribution of the study lies in showing how monetary transmission in a transition economy may remain constrained even after formal regime modernization. Future research should extend the analysis using disaggregated bank-rate data,

explicit break tests, richer controls, and nonlinear specifications capable of identifying asymmetry directly.

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THEORETICAL FOUNDATIONS OF THE INTERACTION BETWEEN FISCAL AND MONETARY POLICIES UNDER WAVES OF OPTIMISM AND PESSIMISM

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Abstract. *In this article, we examine the views of foreign scholars on the interaction of fiscal and monetary policies under the assumption that agents have limited cognitive abilities. Based on the Keynesian model, the theoretical foundations of the studies on the possibility of agents' beliefs being subject to waves of optimism and pessimism under three alternative policy regimes are analyzed. The results of the studies show that there are new approaches to the existence of a strong relationship between output, inflation, government spending and public debt, regardless of the policy regime, with the beliefs of agents. That is, the stability of the system is characterized by constant fluctuations between optimism and pessimism. Along with these views, macroeconomic indicators of the monetary and fiscal strategies of the Republic of Uzbekistan are analyzed and scientific conclusions are drawn.*

Keywords: *fiscal policy, monetary policy, waves of optimism and pessimism, behavioral macroeconomics, fiscal surplus, monetary surplus, macroeconomic stability.*

Introduction

In a period when the joint role and importance of fiscal and monetary policies in stabilizing the economy is increasing, special attention is paid to developing the right policy mix in scientific research. It has also been emphasized that ensuring the mutual compatibility of these policies serves as the key to sustainable development in the future. Such studies include studying the interaction of fiscal and monetary policies through dynamic (Saltari et al., 2021) and static (Foresti, 2018) analyses. That is, these policies are emphasized as measures taken to eliminate the consequences of imperfectly competitive markets.

The importance of such analyses is also supported by recent empirical studies, which show that different dominance regimes exist in different countries. Fragetta and Kirsanova (2010) show that the UK and Sweden have a fiscal dominance regime, while in the US, government agencies interact without dominance, so their interactions are better described by a Nash equilibrium. Also, different structures of the interaction between fiscal and monetary policies have different effects on the outcomes of the policy mix and its institutional organization. In comparison with the Nash equilibrium, fiscal superiority can improve the outcomes of the policy mix if the central bank pursues a tight policy (Dixit and Lambertini, 2003a).

However, if the fiscal authorities do not sufficiently consider the future or aim for overproduction, the damage caused by the lack of leadership will be even greater (Kirsanova et al., 2005). In a Nash equilibrium, the two policies are implemented independently and are considered to be mutually incompatible. The theoretical approach in the article mainly studies the effects of different policy regimes under the assumption that agents follow simple heuristic rules in forming their expectations about the future. In this, we mainly assume that “agents form their expectations in a behavioral way,” as emphasized in the research of Peter Flaschel (Flaschel et al.,

2015; 2018). Flaschel et al. (2015) assume that agents can be fundamentalists or extrapolators in forming their expectations.

Third, it introduces an element of rationality by allowing agents to revise their forecasting rules. The applied learning mechanism generates endogenous waves of optimism and pessimism, as shown in Flaschel et al. (2018). At the same time, the theoretical basis of how the economy stabilizes under different combinations of fiscal and monetary policies in the presence of these destabilizing waves is analyzed (Chiarella et al., 2005; 2012, Choriev, 2024).

Literature review. The narrow scope of macroeconomic models for sustainable economic growth limits the ability to draw conclusions that are appropriate for the next stages of development. In this regard, it is not enough to draw conclusions using the RBS model and DSGE models to analyze the causes and effects of business cycle oscillations. As a modern economic approach, behavioral macroeconomics is giving rise to the use of new economic terms. This theory is based on the rational individual paradigm, introducing an element of rationality in such a way that individuals learn from their mistakes and switch to rules that give better results. This approach puts forward the idea of endogenously formed “animal spirits” - “spiritual moods”, that is, waves of optimism and pessimism, which drive the business cycle and are also affected by it, and uses this model to shed new light on a number of important issues (De Grauwe et al., 2019).

Also, much of the literature assumes that the government can subsidize factors of production in order to eliminate the inefficiencies caused by imperfect competition in the markets for goods and services and economic factors, and that this subsidy is financed by one-time taxes. This assumption is clearly unrealistic from a practical, that is, empirical, point of view. More importantly, such an approach weakens the potentially important role of monetary policy, namely the role of stabilizing the cost-effective aggregate fluctuations around the disturbed stationary equilibrium.

From the works of Keynes (1936) and Hicks (1939) to the studies of Kydland and Prescott (1982), macroeconomic theories have emphasized investment dynamics as an important channel for the transmission of aggregate shocks. Therefore, it is natural that investment spending plays an important role in the formation of optimal monetary policy. Indeed, it has been shown that the properties of the rational expectations equilibrium can change dramatically when the assumption of capital accumulation is added to the standard New Keynesian model under a given monetary regime (Dupor, 2001; Carlstrom and Fuerst, 2005).

Existing studies also deviate from real-world practice when it comes to the fiscal regime. It is common practice in this literature to completely ignore fiscal policy. Such models implicitly assume that the fiscal budget is always balanced by lump-sum taxes. In other words, fiscal policy is not always disruptive, and as Leeper (1991) argues, policies are characterized as “active” or “passive” depending on the extent to which they respond to shocks to the government debt. However, empirical studies such as Favero and Monacelli (2003) show that the description of postwar US fiscal policy as always passive is inconsistent with the facts. Moreover, it is well known from theory that the properties of the rational expectations equilibrium given monetary policy depend strongly on the nature of the fiscal policy. Thus, the optimal design of monetary policy should depend strongly on the fiscal regime in place. The implication is that the coherence of policies that are made independently of each other is expressed in terms of their coherence.

Analysis based on the optimal monetary policy model is usually limited to economies with stable long-term inflation. As a result, nominal rigidities do not have a real impact on economic activity and welfare in the long run. It follows that it is wrong to assume that assumptions about

zero long-term inflation or the existence of indexation have no impact on the optimal monetary policy form.

The existence of endogenous fluctuations of optimism and pessimism, or "animal spirits," is important for monetary policy. Its consequences are analyzed by constructing a trade-off between output and inflation volatility. In standard DSGE models, this trade-off is always downward biased. This means that in such models, any attempt to reduce output volatility through the interest rate instrument comes at a cost, namely increased inflation volatility. In other words, if monetary authorities increase their desire to stabilize output volatility, they may succeed in reducing output volatility, but at the expense of increasing inflation volatility (Grauwe and Macchiarelli, 2015).

Methodology

This article analyzes the theoretical foundations of scientific works, summarizes them, and draws conclusions. These studies consider what changes will occur in the economy under a certain regime of policies, and the methods of induction and deduction are used in the research. Also, analyses are carried out based on the monetary and fiscal strategies of our Republic. Scientifically based conclusions are formed on these analyses.

Analysis and results

The model developed in Grauwe and Macchiarelli's (2015) research is based on a micro-based, New Keynesian model with heterogeneous agents. The economy is described by aggregate demand, the Phillips curve, and the government debt equation. Forecasts of output, inflation, and government spending are formulated based on simple heuristics, i.e., inferences based on initial data. Thanks to the learning mechanism, the model generates endogenous waves of optimism and pessimism, i.e., animal spirits - the general mental state of agents, and fiscal beliefs - the trust and expectations in the government's fiscal policy.

Monetary and fiscal policies operate through separate mandates and for separate purposes, and they interact in a non-corporate manner. This approach is based on the model used in De Grauwe and Kirsanova (2010). It is methodologically convenient to express the strategic interaction between fiscal and monetary authorities as a linear-quadratic optimization problem, since its solution is usually obtained in the form of two linear response functions. This approach, while simplifying the model, allows us to clearly show how monetary and fiscal instruments interact in different policy regimes. In general, if the main instrument of the Central Bank is the interest rate, the government implements fiscal policy by changing government spending. We also define the policy structures in three alternative interaction regimes, namely fiscal dominance (FD), monetary dominance (MD), and no dominance (ND), as follows:

Lack of dominance In the ND regime, the authorities make decisions simultaneously, without taking into account each other's reactions. This means that the fiscal policy instrument in the current period does not directly affect the monetary decisions, and the monetary policy instrument in the current period does not directly affect the fiscal policy. However, assuming that there is a smoothing of policy instruments, each policy rule is affected by the policy instrument of the other authority with a delay. This follows from the fact that if the authorities smooth their policy instruments, the policy variables of the past period become predetermined state variables.

In the fiscal dominance (FD) regime, the fiscal authority plays a leading role and can influence monetary policy. This means that the fiscal variable in the current period is included in the monetary policy rule. At the same time, the interest rate in the current period is not part of the

fiscal rule, since the government, due to its dominant position, determines government spending independently of the decisions of the central bank.

In the monetary dominance (MD) regime, the central bank plays a leading role and influences fiscal decisions. This means that the current period monetary policy variable affects fiscal decisions and is therefore part of the fiscal rule. At the same time, the current period fiscal policy variable does not affect monetary policy, since in this case the policy decisions are made by the central bank, not the government.

The fiscal rule follows a similar logic. In this case, the government responds to the variables of interest with a one-period lag, since it takes time to implement fiscal adjustments (Muscatelli and Tirelli, 2005). This reflects the fact that fiscal decisions are usually made at a lower frequency than monetary policy. Following the work of Fragetta and Kirsanova (2010), we define the parameters as follows. In the ND regime, the authorities act without taking into account each other's reactions. This means that the current period interest rate and government spending do not directly affect each other. However, since we assume that the authorities smooth their policy instruments, there are lagged variables in both equations. In the FD regime, the fiscal authorities can affect the current period interest rate.

Simultaneously, fiscal and monetary policies for 2026-2028 have been developed and approved for the sustainable development of the economy. In developing these strategies, an analysis of the current state of macroeconomic indicators and their forecasts were presented, and strategic directions were determined based on these indicators. When determining the strategic indicators of monetary policy for the coming years, it was assumed that domestic conditions would stabilize aggregate demand, moderate lending processes, increase wages proportional to labor productivity, return remittance growth to the medium-term trajectory, stable investment flows, and the fiscal deficit would not exceed 3 percent of GDP in the medium term.

According to the main monetary policy scenario, real GDP growth is projected at 5.5-6.5 percent in 2026, and 6-7 percent in 2027-2028. Even under the main macroeconomic development scenario and other shocks, monetary policy will implement measures aimed at reducing inflation to the 5 percent target level. Headline inflation is projected to reach 7 percent by the end of 2026, to decrease to the 5 percent target level in 2027 as a result of reduced external inflationary pressure and stabilization of inflation expectations, and to remain around this level from 2028. In order to ensure macroeconomic stability, it is aimed to implement measures aimed at increasing the country's sovereign credit rating and entering the ranks of upper-middle-income countries by increasing the volume of gross domestic product to $200 billion and per capita income to $5,000. It is also determined to diversify the public debt portfolio and manage currency risks in order to effectively manage public debt, as well as ensure that the ratio of public debt to GDP does not exceed 50 percent through the implementation of the public debt management strategy for 2026-2028.

Table 1

Table 1. Global macroeconomic indicators forecast for 2026-2028 under the base scenario

Indicators	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
World GDP growth, %	3,5	3,3	3,2	3,1	3,2	3,2
Global inflation, %	6,0	4,9	4,0	3,5	3,4	3,2
Gold price, average annual, uns/dollar	1 943	2 388	3 428	3 983	3 500	3 410

According to the Central Bank, the growth trends in the world economy are projected to be around 3.1-3.2 percent for 2026-2028. Also, the trends of a decrease in the global inflation rate from 4 percent to 3.2 percent require the adoption of certain significant monetary measures. Also, the forecasts of a downward trend in the price of gold in the world market, in turn, require taking into account macro-fiscal risks when developing fiscal strategies. It is also important to adhere to certain established fiscal rules.

There are also risks of an increase in the fiscal deficit as a result of the imbalance between budget expenditures and revenues. The formation of a fiscal deficit above 3 percent of GDP increases aggregate demand in the economy and creates additional inflationary pressure.

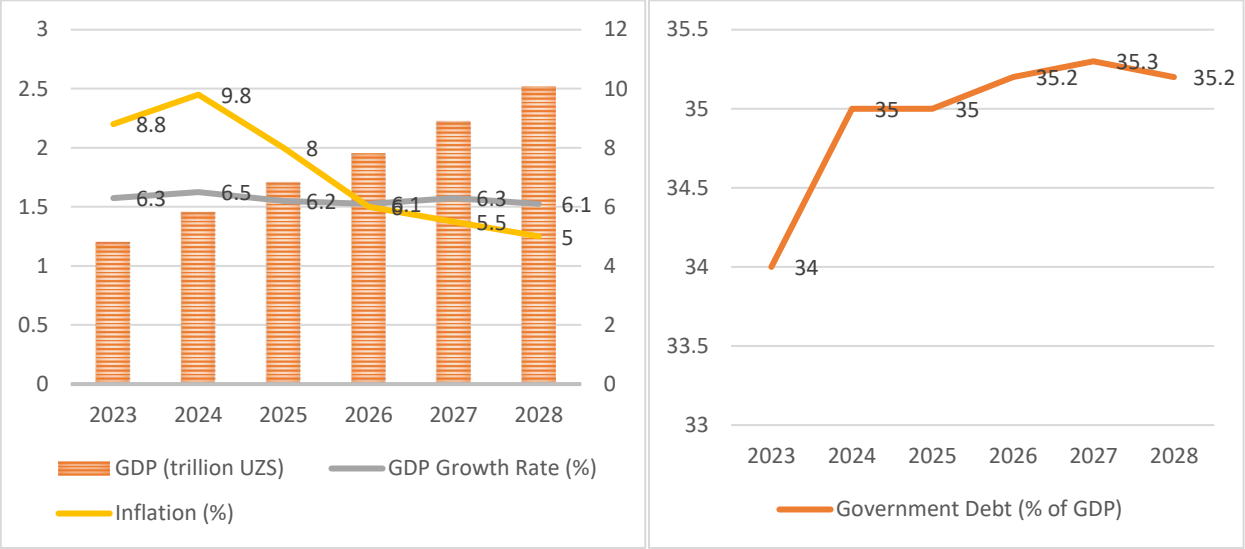


Figure 1. Forecasts of macroeconomic development indicators of Uzbekistan for 2026-2028 according to the base scenario

The GDP growth rate of the Republic of Uzbekistan for 2026-2028 is projected to be around 6.1 percent, with GDP expected to increase from 1,954 trillion soums in 2026 to 2,520 trillion soums in 2028. The balance of public debt as of January 1, 2025 amounted to 40.2 billion US dollars, of which public external debt - 33.7 billion US dollars, public domestic debt - 6.5 billion US dollars, or 35 percent of GDP. It has been determined to implement measures aimed at maintaining this percentage share in the coming years. Under the influence of the formation of a fiscal deficit of around 5 percent of GDP, the inflation rate may be 0.7-0.9 percentage points higher than in the baseline scenario, and the GDP level may be 0.6-0.7 percentage points higher. In the event of a fiscal deficit higher than in the baseline scenario, there is a need to take measures to further tighten monetary policy. In this regard, the structural direction of fiscal policy is of great importance.

In particular, even if the fiscal deficit is relatively “normal”, that is, around 3 percent of GDP, if government spending is increased in conditions where the economy is showing high growth rates and there is a risk of “overheating”, such a policy will in fact take on a procyclical nature. This will increase existing inflationary pressures and reduce the effectiveness of monetary policy. In this case, it is important to conduct fiscal policy in a countercyclical manner, that is, based on budget rules tied to economic activity. During periods of high economic activity, it is important not to sharply increase spending compared to the plan and to maintain financial discipline.

Conclusion

In the implementation of key measures aimed at ensuring macroeconomic stability, measures will be taken to create conditions for the formation of general inflation at 6-7 percent in 2026 and core inflation at around 5-6 percent, and general inflation at around 5 percent from 2027, based on the widespread introduction of targeted inflation control mechanisms. In ensuring fiscal stability, fiscal rules will be strictly followed. In this regard, measures will be taken to reduce the consolidated budget deficit to 3 percent of GDP, improve tax administration, reduce the share of the shadow economy and increase the revenue base by eliminating ineffective tax incentives, ensure targeted and rational targeting of state spending, reduce ineffective budget loans and subsidies, and increase spending efficiency.

Effective management of public debt and contingent liabilities will be strictly implemented on the basis of target limit rules, whereby measures will be taken not to exceed the limit set for 2026 for newly signed external debt transactions to ensure that public debt remains at a safe level (50 percent of GDP), and to prevent an increase in fiscal risks on the state's contingent liabilities in the medium term, measures will be taken not to exceed the limit amounts for newly signed PPP projects in 2026. The success of fiscal and monetary policy strategies for 2026–2028 directly depends not only on official macroeconomic indicators and their instruments, but also on the expectations, confidence and behavior of economic agents. In particular, if consumers, entrepreneurs and investors form positive expectations about future inflation, economic growth, incomes and financial stability, this will accelerate the achievement of strategic goals through investment activity, consumption and an improvement in the business environment. On the contrary, increased uncertainty, weakening of fiscal discipline or worsening inflationary expectations can increase pessimistic sentiment and reduce the effectiveness of economic decisions. Therefore, in order to ensure macroeconomic stability, in addition to the coordination of fiscal and monetary policies, strengthening the confidence of economic agents, stable formation of expectations and creating a positive environment among market participants are also important strategic tasks.

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ECONOMIC EFFICIENCY OF BEE COLONIES

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Abstract. *In the article, indicators such as the productivity of bee colonies, honey production, and their economic efficiency were studied and analyzed based on comparative experiments.*

Keywords*: bee, sugar syrup, honey, production, protein feed, bee colony, indicators, costs, income, profitability, net profit, economic efficiency.*

I. INTRODUCTION

It is widely acknowledged that the economic efficiency of the industry producing high-quality honey and beekeeping products depends on the bee breed, variety, care and maintenance technology, natural and climatic conditions, season, natural food sources, off-season feeding, colony age and size, compliance with veterinary and sanitary regulations, and other factors [2, 3, 4]. For improving the economic efficiency of breeding and maintaining bee colonies in Uzbekistan, it is necessary to properly prepare them for wintering in the second half of August, September, and October, as the main losses in beekeeping occur in winter and average 12-14% of the total number of colonies [5, 6].

Colonies that survive a harsh winter cause significant damage to beekeeping, while bee diseases, in turn, hinder the development of the industry. Caron, D.M., and Connor, L.J. (2013), Krivsov, N.I., Lebedev, V.I. (2001), Brandor, A.Z. (2012), Korolev V.P. (2012), Kurchavenkov A.B. (2012), Nuzhdin A.S. (2005), Skvorsov A.I. (2011), Turaev O.S. (2010), Eshadavlatov O.Z. (2021), Nurmurodova N.F. (2025). One of the reasons for the low winter survival of bees is that during the winter, bees are unable to leave the hive to clean their intestines; feces accumulate in their large intestine, increasing the fecal load in the intestines, which leads to diarrhea and even death. The main aspect of beekeeping is the preservation of bee colonies during the winter, when bees are closely grouped and their activity decreases. Mannapov A. G., Larionova O. S., Smolnikova E. A. (2011), Khudaiberdiev A. A. (2020), Kononenko E. A., Moreva L. Ya. (2021), Ishmuratova N. M., Tambovsev K. A. (2021).

Beekeeping primarily requires the production of large quantities of high-quality products, increased income, and net profit by reducing production costs. Numerous studies have shown that the main factors for increasing bee colony productivity are raising queen bees in early spring, forming bee colonies and producing bee packages, intensive feeding methods, and improving economic efficiency [13, 14, 15]. It is important to conduct scientific research into the scientific foundations of technologies that accelerate bee colony maintenance and increase their productivity.

II. RESEARCH MATERIAL AND METHOD.

The study was conducted from 2023 to 2025 at the educational and experimental farm of the TDAU in the Kibray district of the Tashkent region, experimental group 1 in the Bustonlyk district of the Tashkent region, and experimental group 2 at apiaries in the Parkent district of the Tashkent region [4]. The data obtained were statistically processed using the Student's t-test,

according to the method of E.K. Merkureva (1970, 1991), and the significance level (R). The calculations were correlated on a computer using MS OFFICE (Microsoft Excel).

III. RESULTS OF THE STUDY.

For implementing the results of our study in production, it is also important to study their economic effectiveness. For this purpose, we examined the economic efficiency of our study. Therefore, special attention was paid to the processes of transplanting bee colonies and the efficient use of their honey collection capacity. All farm conditions were taken into account for the growth and development of bee colonies in the experiment. The costs of establishing and replanting one bee colony were calculated. We assessed the economic efficiency of the experimental and control groups based on production costs per season at 2023-2025 prices. The data are presented in Tables 1, 2, and 3.

Table 1

Economic efficiency of the studies.

№	**Indicators**	**2023 year**		
		The groups of bee colonies in the experiment are n-10.		
		1- experimental group	2- experimental group	control group
1	Purchase of a beehive, soums	4000000	4000000	4000000
2	Purchase of equipment and supplies used for beekeeping, soums	600000	600000	600000
3	Purchase of medicines against bee pests and diseases, soums	400000	400000	400000
4	Feed consumption for 120 days, soums	4460000	4460000	4260000
5	Costs of relocating bee colonies, soums	500000	500000	-
6	Total production costs, soums	9960000	9960000	9260000
7	Honey production, kg	186	164	142
8	Selling price of 1 kg of honey, soums	70000	70000	70000
9	Revenue from honey sales, soums	13020000	11480000	9940000
10	Net profit, soums	3060000	1520000	680000
11	Profitability ratio, %	30,7	15,2	7,3

As can be seen from the data in Table 1, in 2023, 3060000 soums were earned from the first experimental group, 1520000 soums from the second experimental group, and 680000 soums from the control group. The profitability level was 30.7% in the first experimental group, 15.2% in the second experimental group, and 7.3% in the control group. The first experimental group was 15.5% higher than the second experimental group and 23.4% higher than the control group. In 2023, equipment and supplies used for beehives and beekeeping were purchased. Despite this, high income was received from bee colonies in all groups.

Table 2

Economic efficiency of the conducted studies.

№	**Indicators**	**2024 year**		
		The groups of bee colonies in the experiment are n-10.		
		1- experimental group	2- experimental group	control group
1	Buy rum, soums	1500000	1500000	1500000
2	Purchase in Mumpar, soums	1200000	1200000	1200000
3	Purchase of medicines against bee pests and diseases, soums	500000	500000	500000
4	Feed consumption for 120 days, soums	5825000	5825000	5625000
5	Costs of relocating bee colonies, soums	500000	500000	-
6	Total production costs, soums	9525000	9525000	8825000
5	Honey production, kg	184	170	151
6	Selling price of 1 kg of honey, soums	75000	75000	75000
7	Revenue from honey sales, soums	13800000	12750000	11325000
8	Net profit, soums	4275000	3225000	2500000
9	Profitability ratio, %	44,9	33,8	28,3

According to Table 2, in the 2024 economic efficiency analysis, the first experimental group outperformed the second experimental group. The first experimental group earned 4,275,000 soums, the second experimental group earned 3,225,000 soums, and the control group earned 2,500,000 soums in net profit. The profitability rate was 44.9% in the first experimental group, 33.8% in the second experimental group, and 28.3% in the control group. The first experimental group outperformed the second experimental group by 11.1% and the control group by 16.6%.

Table 3

Economic efficiency of the studies.

№	**Indicators**	**2025 year**		
		The groups of bee colonies in the experiment are n-10.		
		1- experimental group	2- experimental group	control group
1	Buy rum, soums	1500000	1500000	1500000
2	Purchase in Mumpar, soums	1200000	1200000	1200000
3	Purchase of medicines against bee pests and diseases, soums	500000	500000	500000
4	Feed consumption for 120 days, soums	5825000	5825000	5625000

5	Costs of relocating bee colonies, soums	600000	600000	-
6	Total production costs, soums	9625000	9625000	8825000
5	Honey production, kg	190	182	160
6	Selling price of 1 kg of honey, soums	80000	80000	80000
7	Revenue from honey sales, soums	15200000	14560000	12800000
8	Net profit, soums	5575000	4935000	3975000
9	Profitability ratio, %	57,9	51,3	45

It should be emphasized that Table 3, which presents economic indicators for 2025, shows that in the third year, the first experimental group earned 5,575,000 soums in net profit, the second experimental group earned 4,935,000 soums, and the control group earned 3,975,000 soums. The profitability rate was 57.9% in the first experimental group, 51.3% in the second experimental group, and 45% in the control group. In the first experimental group, this indicator was 6.6% higher than in the second experimental group and 12.9% higher than in the control group. The results of our study, taken from the works of N. I. Krivsov, V. I. Lebedev (2001), A. Z. Brandorf (2012), A. G. Mannapov, O. S. Larionova, E. A. Smolnikova (2011), A. A. Khudaiberdiev (2020), O. Z. Eshdavlatov (2021), and N. F. Nurmurodova (2025), are consistent with the results obtained during scientific research. The authors studied the economic efficiency of honey production obtained from bee colonies of different breeds.

IV. CONCLUSIONS.

According to the results of scientific research, the productivity of the first experimental group of Krajina bees was high in all three years. The data obtained showed that feeding bee colonies with protein feed in spring and autumn, as well as the use of Krajina and Carpathian bees in beekeeping farms, is economically feasible.

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