

ISSN-2222-5013

SCIENTIFIC WORKS



**AZERBAIJAN UNIVERSITY OF
ARCHITECTURE AND CONSTRUCTION**



SW AZUAC

<https://swjournal.az>

No.2 / 2025



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<https://doi.org/10.58225/sw.2025.2-4-16>

HIGHER-ORDER THEORIES FOR DOUBLY-CURVED LAMINATED ANISOTROPIC SHELL STRUCTURES WITH GENERALIZED DIFFERENTIAL QUADRATURE METHOD

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Abstract. A refined two-dimensional (2D) formulation is presented for evaluating the static and free vibrational response of laminated anisotropic doubly-curved shell structures. The model is based on a unified formulation and accounts for a kinematic model which uses higher-order polynomials. The governing equations are derived from the Hamilton principle in principal coordinates, explicitly accounting for curvature effects and arbitrarily shaped external surface loads. A numerical solution is obtained by approximating the strong form governing equations with the Generalized Differential Quadrature (GDQ) method. In the post-processing, the strain and stress distributions of the corresponding three-dimensional (3D) solid are reconstructed through an equilibrium-based recovery procedure. Some numerical examples are provided to validate the model against reference 3D finite-element solutions obtained with commercial software. In addition, the influence of the through-the-thickness kinematic model on the accuracy of the results is assessed for both natural frequency prediction and static response of the laminate. The proposed approach provides an efficient and reliable tool for analyzing doubly-curved laminated structures made of advanced materials, offering high accuracy with reduced computational cost.

Keywords: anisotropic materials, doubly-curved shells, equivalent single layer, generalized differential quadrature

1.Introduction. Novel applications across engineering fields increasingly demand advanced structural models capable of accurately predicting the response of components made from innovative materials and featuring complex geometries, all with reduced computational cost. In the context of laminated structures, two-dimensional (2D) formulations are widely adopted and typically classified into Equivalent Single Layer (ESL) and Layer-Wise (LW) theories. ESL theories reduce the three-dimensional (3D) mechanics of a laminated panel to that of a reference surface located at the mid-thickness of the structure [1], whereas LW theories assign a reference surface to each layer. Consequently, the geometric description of the reference surface becomes a key element of LW models, requiring the use of differential geometry principles—particularly when parametrization in curvilinear principal coordinates is available [2]. In the absence of such parametrization, a mapping of the physical domain must be introduced. Another critical aspect related to 2D formulations is the kinematic model assumed along the thickness direction. Classical approaches, such as Kirchhoff-Love Plate Theory (CPT) and the First-order Shear Deformation Theory (FSDT), assume linear through-the-thickness distributions of the in-plane displacement field variables, while assigning a uniform distribution to the out-of-plane displacement. To improve the accuracy, the Third-order Shear Deformation Theory (TSDT) introduces a third-order polynomial for in-plane displacements. To overcome the limitations of classical approaches, higher-order theories have been introduced, which employ higher-order polynomials to describe the unknown field variables. Within this framework, the unified formulation has emerged as an effective modeling strategy, introducing generalized thickness functions to construct flexible kinematic models. These higher-order 2D formulations enable more refined predictions than

classical models. Analytical solutions of the governing equations are possible for selected geometries, materials, loads, and boundary conditions, providing efficient benchmarks [3]. However, for most engineering applications, closed-form solutions are not feasible, requiring the adoption of numerical techniques. The Finite Element Method (FEM) remains the most widely used approach but may become computationally expensive, particularly for components with geometric discontinuities or complex boundaries. As an efficient alternative, the Generalized Differential Quadrature (GDQ) method directly discretizes the strong form of the governing equations using a global interpolation of derivatives [4]. This method has proven highly accurate across various engineering problems, achieving excellent agreement with reference solutions while drastically reducing the number of Degrees of Freedom (DOFs) compared to FEM.

In this work, the accuracy of higher-order theories is assessed for the analysis of anisotropic doubly-curved shell structures. The governing equations are derived from the Hamilton principle, considering the elastic strain energy, kinetic energy, and the virtual work of external loads. The kinematic model is based on the unified formulation and incorporates zigzag functions to predict the interaction between adjacent layers. A NURBS-based mapping of the physical domain is introduced to handle arbitrarily-shaped shell geometries. Numerical solutions are obtained with the GDQ method, while post-processing involves reconstructing through-thickness strain and stress distributions using a recovery procedure [5] based on 3D equilibrium equations. Natural frequencies are also determined. The validation is carried out by comparing the GDQ predictions against 3D FEM reference solutions [6] obtained from commercial software, confirming the model accuracy for both static and free vibration analyses. The influence of the kinematic expansion order is further examined. Overall, the proposed formulation provides an efficient and reliable tool for analyzing laminated structural components of complex shape, combining the accuracy of higher-order theories with the computational efficiency of GDQ.

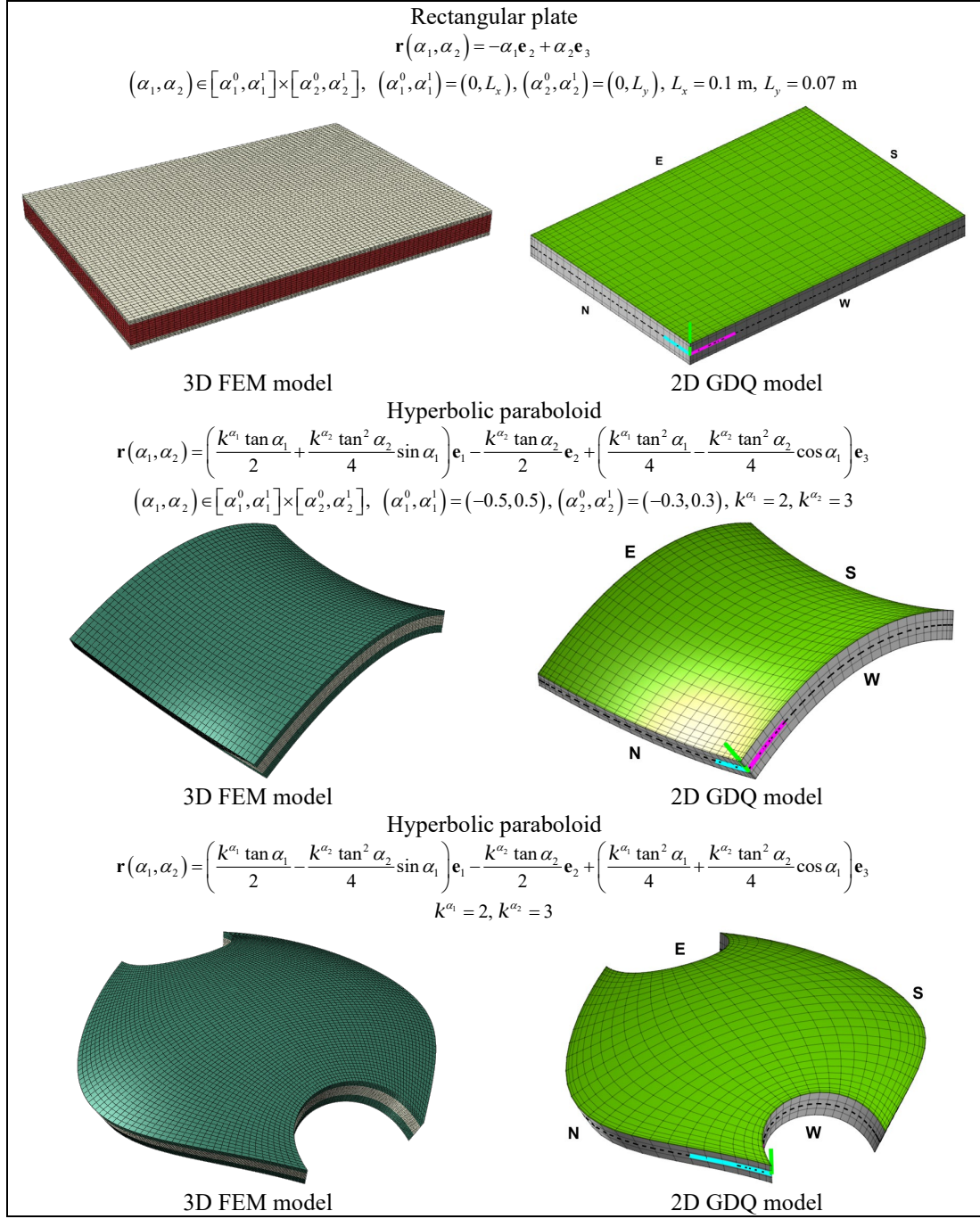


Figure 1. Position vector and representation of the laminated structures considered in the simulation.

Theoretical formulation. In this section, the theoretical framework for the adoption of higher-order theories for the static and dynamic analysis of laminated shell structures is briefly outlined. The formulation begins with the geometric description of the structure in an appropriate system of curvilinear principal coordinates. Within this setting, the main geometric features of the reference surface, represented by its position vector $\mathbf{r}(\alpha_1, \alpha_2)$, are derived using the main principles of differential geometry. These quantities include the Lamé parameters A_1, A_2 , and the principal radii of curvature R_1, R_2 , among others. An arbitrary point of the doubly-curved 3D solid can, thus, be expressed in terms of the position vector $\mathbf{R}$, defined as:

$$\mathbf{R}(\alpha_1, \alpha_2, \zeta) = \mathbf{r}(\alpha_1, \alpha_2) + \frac{h(\alpha_1, \alpha_2)}{2} \mathbf{z} \mathbf{n}(\alpha_1, \alpha_2) \quad (1)$$

In the previous equation, $h(\alpha_1, \alpha_2)$ denotes the total thickness of the structure, obtained as the sum of the thicknesses h_k with $k=1, \dots, l$ of each layer in the lamination scheme, while $z = 2\zeta/h$ is a dimensionless thickness coordinate. The vector $\mathbf{n}(\alpha_1, \alpha_2)$ represents the outward normal unit vector to the reference surface. The geometric coordinates in Eq. (1) are, therefore, the principal directions α_1, α_2 of the reference surface, which vary within the rectangular interval $[\alpha_1^0, \alpha_1^1] \times [\alpha_2^0, \alpha_2^1]$, together with the thickness coordinate ζ , with $\zeta \in [-h/2, h/2]$. In case of arbitrarily-shaped structures that cannot be described using principal coordinates, a generalized mapping procedure is employed. This approach is based on blending functions that use NURBS curves to represent the arbitrary geometry. Accordingly, the natural coordinates ξ_1, ξ_2 are introduced, which vary within a dimensionless parent element $[-1, 1]$.

$$\begin{aligned} \alpha_1(\xi_1, \xi_2) &= \frac{1}{2} \left((1-\xi_2) \bar{\alpha}_{1(1)}(\xi_1) + (1+\xi_1) \bar{\alpha}_{1(2)}(\xi_2) + (1+\xi_2) \bar{\alpha}_{1(3)}(\xi_1) + (1-\xi_1) \bar{\alpha}_{1(4)}(\xi_2) \right) + \\ &\quad - \frac{1}{4} \left((1-\xi_1)(1-\xi_2) \alpha_{1(1)} + (1+\xi_1)(1-\xi_2) \alpha_{1(2)} + (1+\xi_1)(1+\xi_2) \alpha_{1(3)} + (1-\xi_1)(1+\xi_2) \alpha_{1(4)} \right) \\ \alpha_2(\xi_1, \xi_2) &= \frac{1}{2} \left((1-\xi_2) \bar{\alpha}_{2(1)}(\xi_1) + (1+\xi_1) \bar{\alpha}_{2(2)}(\xi_2) + (1+\xi_2) \bar{\alpha}_{2(3)}(\xi_1) + (1-\xi_1) \bar{\alpha}_{2(4)}(\xi_2) \right) + \\ &\quad - \frac{1}{4} \left((1-\xi_1)(1-\xi_2) \alpha_{2(1)} + (1+\xi_1)(1-\xi_2) \alpha_{2(2)} + (1+\xi_1)(1+\xi_2) \alpha_{2(3)} + (1-\xi_1)(1+\xi_2) \alpha_{2(4)} \right) \end{aligned} \quad (2)$$

In line with the ESL modeling of laminated structures, the displacement field variables, arranged in the vector $\mathbf{U}^{(k)} = [U_1^{(k)} \ U_2^{(k)} \ U_3^{(k)}]^T$, are expanded in terms of generalized thickness functions $F^{(k\tau)\alpha_i}$ with $i=1, 2, 3$, defined for any $\tau=0, \dots, N+1$. In a compact form, this can be expressed as:

$$\mathbf{U}^{(k)}(\alpha_1, \alpha_2, \zeta, t) = \sum_{\tau=0}^{N+1} \mathbf{F}^{(k\tau)} \mathbf{u}^{(\tau)} \quad (3)$$

where $\mathbf{u}^{(\tau)} = [u_1^{(\tau)} \ u_2^{(\tau)} \ u_3^{(\tau)}]^T$ is the vector of the generalized displacement field components defined on the reference surface, while $\mathbf{F}^{(k\tau)}$ is the thickness function matrix, of size 3×3 , for any $\tau=0, \dots, N+1$. In this work, the thickness functions are constructed using power polynomials for $\tau=0, \dots, N$. In addition, for $\tau=N+1$, the Murakami's function is used, which enables the representation of the well-known zigzag effect:

$$F_i^{(k)\alpha_i}(\zeta) = \begin{cases} \zeta^\tau & \tau = 0, \dots, N \\ (-1)^k z_k = (-1)^k \frac{2}{\zeta_{k+1} - \zeta_k} \zeta - \frac{\zeta_{k+1} + \zeta_k}{\zeta_{k+1} - \zeta_k} & \tau = N+1 \end{cases} \quad (4)$$

Starting from the kinematic model introduced in Eq. (3), the strain-displacement are derived. By using higher-order theories, the 3D strain vector $\mathbf{\epsilon}^{(k)}(\alpha_1, \alpha_2, \zeta, t) = [\epsilon_1^{(k)} \ \epsilon_2^{(k)} \ \gamma_{12}^{(k)} \ \gamma_{13}^{(k)} \ \gamma_{23}^{(k)} \ \epsilon_3^{(k)}]^T$ is expanded as follows, where $\mathbf{\epsilon}^{(\tau)\alpha_i} = [\epsilon_1^{(\tau)\alpha_i} \ \epsilon_2^{(\tau)\alpha_i} \ \gamma_{12}^{(\tau)\alpha_i} \ \gamma_{13}^{(\tau)\alpha_i} \ \gamma_{23}^{(\tau)\alpha_i} \ \omega_{13}^{(\tau)\alpha_i} \ \omega_{23}^{(\tau)\alpha_i} \ \epsilon_3^{(\tau)\alpha_i}]^T$ is the vector of the generalized strain components:

$$\mathbf{\epsilon}^{(k)} = \sum_{\tau=0}^{N+1} \sum_{i=1}^3 \mathbf{Z}^{(k\tau)\alpha_i} \mathbf{\epsilon}^{(\tau)\alpha_i} \quad (5)$$

Additional details on the derivation of the generalized definition operator $\mathbf{Z}^{(k\tau)\alpha_i}$ in Eq. (5) can be found in Ref. [4]. The constitutive relationship adopted in this theory accounts for a generally anisotropic behavior at each point of the 3D solid, in line with the expression reported below:

$$\boldsymbol{\sigma}^{(k)} = \bar{\mathbf{E}}^{(k)} \mathbf{\epsilon}^{(k)} \leftrightarrow \begin{bmatrix} \sigma_1^{(k)} \\ \sigma_2^{(k)} \\ \tau_{12}^{(k)} \\ \tau_{13}^{(k)} \\ \tau_{23}^{(k)} \\ \sigma_3^{(k)} \end{bmatrix} = \begin{bmatrix} \bar{E}_{11}^{(k)} & \bar{E}_{12}^{(k)} & \bar{E}_{16}^{(k)} & \bar{E}_{14}^{(k)} & \bar{E}_{15}^{(k)} & \bar{E}_{13}^{(k)} \\ \bar{E}_{12}^{(k)} & \bar{E}_{22}^{(k)} & \bar{E}_{26}^{(k)} & \bar{E}_{24}^{(k)} & \bar{E}_{25}^{(k)} & \bar{E}_{23}^{(k)} \\ \bar{E}_{16}^{(k)} & \bar{E}_{26}^{(k)} & \bar{E}_{66}^{(k)} & \bar{E}_{46}^{(k)} & \bar{E}_{56}^{(k)} & \bar{E}_{36}^{(k)} \\ \bar{E}_{14}^{(k)} & \bar{E}_{24}^{(k)} & \bar{E}_{46}^{(k)} & \bar{E}_{44}^{(k)} & \bar{E}_{45}^{(k)} & \bar{E}_{34}^{(k)} \\ \bar{E}_{15}^{(k)} & \bar{E}_{25}^{(k)} & \bar{E}_{56}^{(k)} & \bar{E}_{45}^{(k)} & \bar{E}_{55}^{(k)} & \bar{E}_{35}^{(k)} \\ \bar{E}_{13}^{(k)} & \bar{E}_{23}^{(k)} & \bar{E}_{36}^{(k)} & \bar{E}_{34}^{(k)} & \bar{E}_{35}^{(k)} & \bar{E}_{33}^{(k)} \end{bmatrix} \begin{bmatrix} \epsilon_1^{(k)} \\ \epsilon_2^{(k)} \\ \gamma_{12}^{(k)} \\ \gamma_{13}^{(k)} \\ \gamma_{23}^{(k)} \\ \epsilon_3^{(k)} \end{bmatrix} \quad (6)$$

with $k=1, \dots, l$. In the previous equation, $\boldsymbol{\sigma}^{(k)}$ denotes the vector of 3D stress components, while $\bar{\mathbf{E}}^{(k)}$ represents the 3D stiffness matrix expressed in the geometric reference system. This matrix is obtained by rotating the stiffness matrix of each individual layer, $\mathbf{E}^{(k)}$, from the material reference system to the geometric reference system through an angle $\vartheta^{(k)}$. To this end, the rotation matrix $\mathbf{T}^{(k)} = \mathbf{T}^{(k)}(\vartheta^{(k)})$ is conveniently introduced. It gives:

$$\bar{\mathbf{E}}^{(k)} = \mathbf{T}^{(k)} \mathbf{E}^{(k)} (\mathbf{T}^{(k)})^T \quad (7)$$

From the computation of the virtual variation of the elastic strain energy, generalized stress components are defined for each τ -th order of the kinematic expansion. These quantities are grouped into the vector $\mathbf{S}^{(\tau)\alpha_i} = [N_1^{(\tau)\alpha_i} \ N_2^{(\tau)\alpha_i} \ N_{12}^{(\tau)\alpha_i} \ N_{21}^{(\tau)\alpha_i} \ T_1^{(\tau)\alpha_i} \ T_2^{(\tau)\alpha_i} \ P_1^{(\tau)\alpha_i} \ P_2^{(\tau)\alpha_i} \ S_3^{(\tau)\alpha_i}]^T$. As a consequence, the 3D constitutive relation in Eq. (6) can be expressed in the ESL formulation as follows:

$$\mathbf{S}^{(\tau)\alpha_i} = \sum_{\eta=0}^{N+1} \sum_{j=1}^3 \mathbf{A}^{(\tau\eta)\alpha_i\alpha_j} \mathbf{\epsilon}^{(\eta)\alpha_j} \quad (8)$$

being $\mathbf{\epsilon}^{(\eta)\alpha_j}$ the higher-order strain vector of Eq. (5), while $\mathbf{A}^{(\tau\eta)\alpha_i\alpha_j}$ denotes the generalized stiffness matrix. Additional details can be found in Ref. [4].

The governing equations are derived from the Hamilton principle by evaluating the elastic strain energy of the 3D solid, the kinetic energy, and the virtual work of external surface loads. By applying the integration by parts rule, the higher-order equilibrium equations are obtained for any τ -th kinematic expansion order, along with the corresponding boundary conditions on the four edges of the 2D physical domain. Then, by introducing the generalized constitutive relation of Eq. (8) the definition equations of Eq. (5), and the kinematic model of Eq. (3), the fundamental

equations are formulated in terms of the generalized displacement field components. These equations can be expressed in compact matrix form in the relation reported below for any $\tau = 0, \dots, N+1$:

$$\sum_{\eta=0}^{N+1} \mathbf{L}^{(\tau\eta)} \mathbf{u}^{(\eta)} - \sum_{\eta=0}^{N+1} \mathbf{M}^{(\tau\eta)} \ddot{\mathbf{u}}^{(\eta)} + \mathbf{q}^{(\tau)} = \mathbf{0} \quad (9)$$

In the previous equation, $\mathbf{L}^{(\tau\eta)}$ denotes the fundamental operator, which incorporates both the equilibrium equations and the definition equations, while $\mathbf{M}^{(\tau\eta)}$ represents the higher-order mass matrix. Finally, the vector $\mathbf{q}^{(\tau)} = [q_1^{(\tau)} \quad q_2^{(\tau)} \quad q_3^{(\tau)}]^T$ contains the generalized surface loads applied on the reference surface, derived from the static equivalence principle by evaluating the virtual work of the loads applied to the top and bottom surfaces of the shell. The complete expressions of these quantities can be found in Ref. [4].

A closed-form analytical solution of the fundamental relations of Eq. (9) can be derived under specific assumptions on geometry, material properties, loading, and boundary conditions, as discussed in Ref. [4]. For more general cases, the solution is computed numerically using the GDQ method. According to the GDQ rule, if $f = f(x)$ is an arbitrary smooth function defined over the closed interval $x \in [a, b]$, the n -th order derivative of f at a discrete point x_i with $i = 1, \dots, I_Q$ is approximated using the following quadrature formula, where $\zeta_{ij}^{(n)}$ are the weighted coefficients, which are calculated recursively [4]:

$$f^{(n)}(x_i) = \left. \frac{\partial^n f(x)}{\partial x^n} \right|_{x=x_i} \cong \sum_{j=1}^{I_Q} \zeta_{ij}^{(n)} f(x_j) \Leftrightarrow \mathbf{f}^{(n)} = \boldsymbol{\zeta}^{(n)} \mathbf{f} \quad (10)$$

The discrete points used in Eq. (10) follow the well-known Chebyshev-Gauss-Lobatto (CGL) distribution, as discussed in detail in Ref. [4]. As a consequence, the size of the discrete vectors $\mathbf{f}^{(n)}$ and $\mathbf{f}$ is $I_Q \times 1$. The matrix form of Eq. (10) also facilitates the extension of the one-dimensional GDQ rule explained above to the 2D case through the use of the Kronecker product.

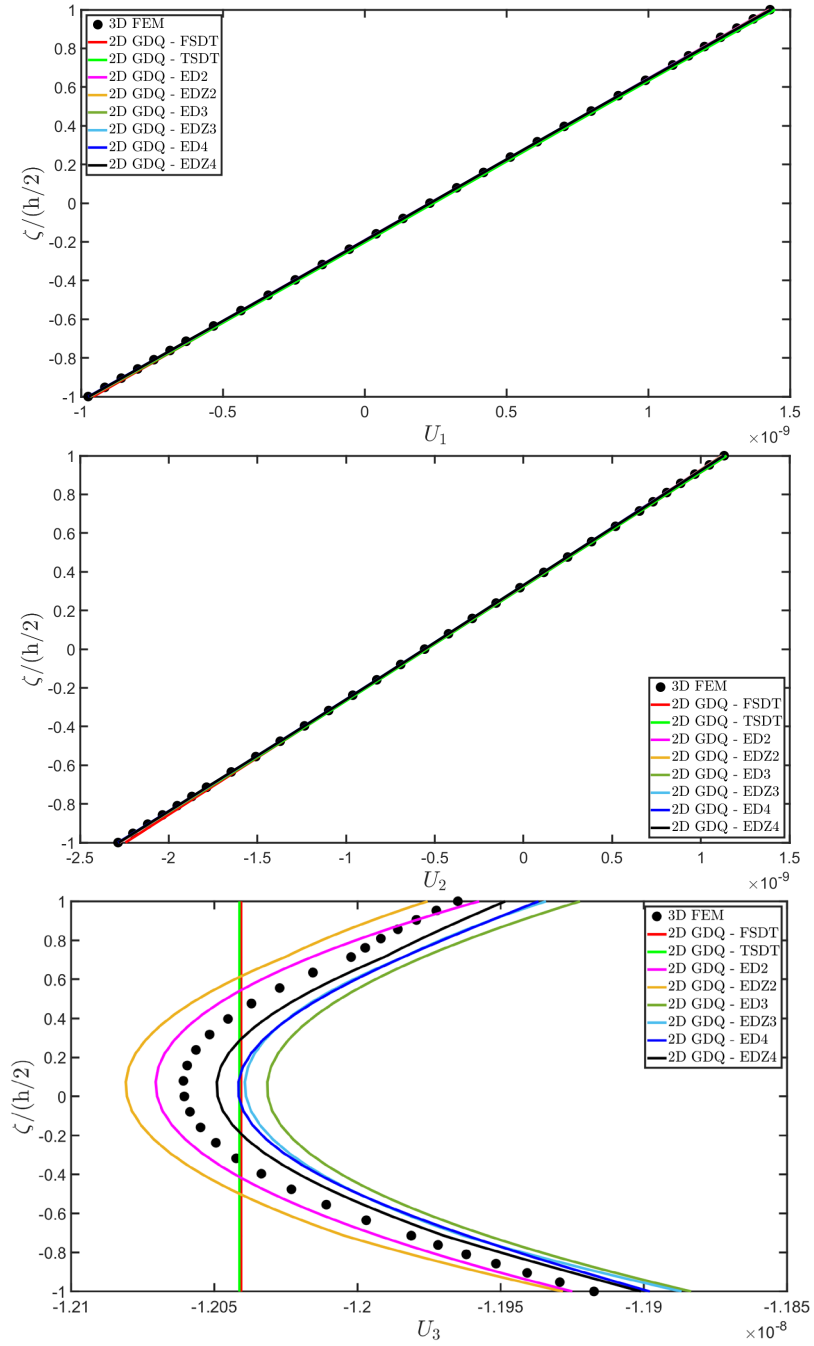


Figure 2. Through-the-thickness distribution of the 3D displacement field components, expressed in m and evaluated at $(0.25L_1, 0.25L_2)$ within the physical domain of a simply-supported rectangular plate made of three layers of generally anisotropic materials subjected to an external pressure and lying on an elastic foundation.

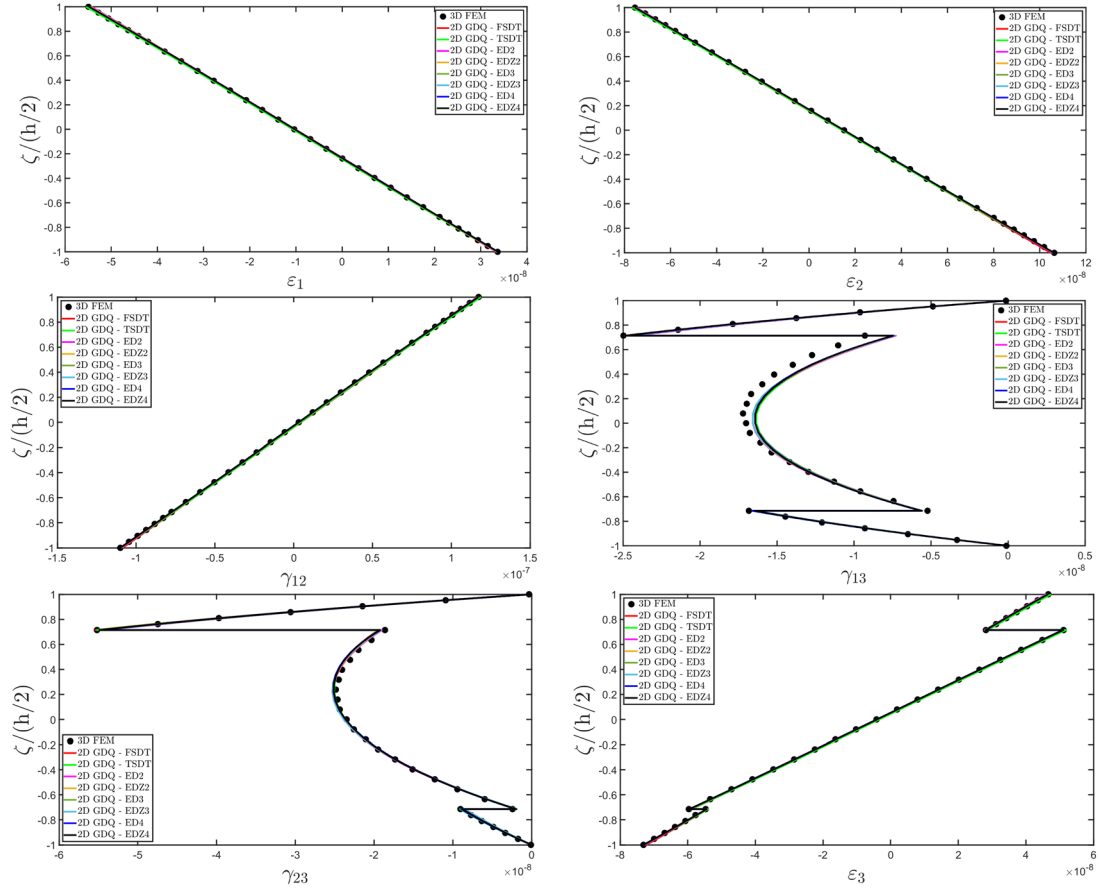


Figure 3. Through-the-thickness distribution of the 3D strain components, expressed in [m/m] and evaluated at $(0.25L_1, 0.25L_2)$ within the physical domain of a simply-supported rectangular plate made of three layers of generally anisotropic materials subjected to an external pressure and lying on an elastic foundation.

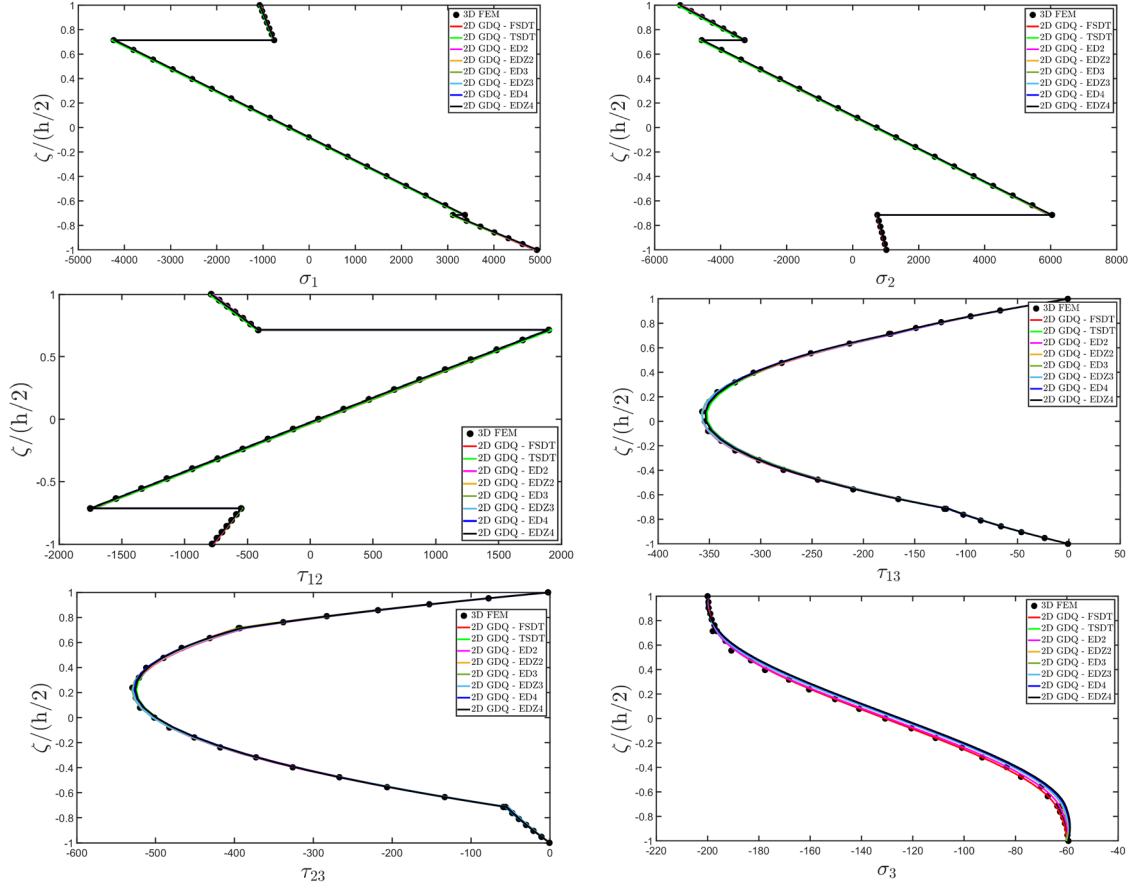


Figure 4. Through-the-thickness distribution of the 3D stress components, expressed in $[\text{N/m}^2]$ and evaluated at $(0.25L_1, 0.25L_2)$ within the physical domain of a simply-supported rectangular plate made of three layers of generally anisotropic materials subjected to an external pressure and lying on an elastic foundation.

Applications and results. In this section, some numerical investigations are presented to assess the structural response of anisotropic panels with different curvatures using the 2D higher-order shell theory. The analysis includes the evaluation of stress and strain distributions, natural frequencies, and mode shapes. For each case, the same analyses are performed using a refined 3D FEM model from commercial software to provide a reference solution. In particular, the panels considered in these investigations are illustrated in Fig. 1. For each panel, the figure provides the reference surface equation for a rectangular plate, an elliptic paraboloid, and a hyperbolic paraboloid, along with a representation of the 3D FEM mesh, which employs parabolic brick elements named C3D20. The 2D GDQ solution is obtained using the well-known CGL distribution, considering a 2D grid made of $I_N \times I_M = 31 \times 31$ sample points. Each structure consists

of three-layers. In particular, the central core is made of triclinic material, and the external laminae are made of graphite-epoxy. The mechanical properties of these materials are taken from Ref. [1].

The first example considers a simply-supported rectangular plate, where the thickness of each lamina is $h_1 = h_3 = 0.001\text{ m}$ and $h_2 = 0.005\text{ m}$. The lamination scheme is $(0/20/70)$. The panel rests on a Winkler elastic foundation, characterized by linear elastic springs oriented along the thickness direction with stiffness $k_{3f}^{(-)} = 5 \times 10^9 \text{ N/m}^3$. A sinusoidally-distributed mechanical pressure of magnitude $\bar{q}_3^{(+)} = 4 \times 10^2 \text{ N/m}^2$ is applied on the top surface, described by the relation reported below:

$$q_3^{(+)}(x, y) = \bar{q}_3^{(+)} \sin\left(\frac{x}{L_1}\right) \sin\left(\frac{y}{L_2}\right) \quad (11)$$

The results are presented in terms of through-the-thickness distributions of the displacement field components, 3D strains, and 3D stress at points located at $(0.25L_1, 0.25L_2)$ within the 2D physical domain, as shown in Figs. 2-4. For each quantity, a 3D FEM solution is provided, as obtained from a numerical model from commercial software, consisting of 65280 elements and 280411 nodes, for a total number of 841233 DOFs. As observed in Fig. 2, the in-plane displacement components exhibit linear distributions, while the out-of-plane component shows a parabolic profile. As a consequence, classical approaches such as FSDT and TSDT cannot be adopted to reproduce results consistent with the 3D FEM solution. On the other hand, the adoption of a higher-order kinematic model significantly improves the accuracy. Increasing the maximum order of the kinematic expansion translates the curve closer to the reference solution, yielding better agreement with the 3D FEM results. On the other hand, the 3D strain components of Fig. 3 predicted by the higher-order model closely match those from the reference solution. The same trend is observed for the 3D stress components in Fig. 4. In particular, the adoption of a higher-order kinematic model, as in the EDZ4 theory, allows for a more accurate evaluation of the out-of-plane stress components through the use of the recovery procedure.

The theory is then applied to determine the natural frequencies and mode shapes of doubly-curved shell structures. In this example, a hyperbolic paraboloid is considered, defined over the rectangular physical domain $(\alpha_1^0, \alpha_1^1) \times (\alpha_2^0, \alpha_2^1) = (-0.5, 0.5) \times (-0.3, 0.3)$, as can be seen from Fig. 1. The lamination scheme consists of two external layers of graphite-epoxy and a central core of triclinic material, oriented according to the stacking sequence $(20/35/75)$. The thicknesses of the three laminae are $h_1 = 0.03\text{ m}$, $h_2 = 0.04\text{ m}$ and $h_3 = 0.02\text{ m}$. The first ten natural frequencies of the panel under consideration are evaluated under CFFF boundary conditions, where C denotes a clamped edge ($u_1^{(r)} = u_2^{(r)} = u_3^{(r)} = 0$), while F denotes the free boundary condition, corresponding to null generalized stress resultants $\mathbf{s}^{(r)\alpha_i}$ along the remaining edges [4]. More specifically, the structure is clamped along the lateral surface corresponding to the edge of the physical domain characterized by $\alpha_2 = \alpha_2^0$. Natural frequencies are reported in Table 1. Here, a successful agreement is shown with the results obtained from a 3D FEM model consisting of 156952 nodes and 36450 elements. In particular, the results demonstrate that the use of a higher-order kinematic model, combined with the zigzag function, is essential to accurately predict the 3D vibrational response of the structure. Finally, Fig. 5 presents a 3D representation of the first nine mode shapes of the structure, obtained from the 2D model employing the EDZ4 kinematic field.

The final numerical example evaluates the accuracy of the theory for arbitrarily-shaped structures. An elliptic paraboloid is considered, with its physical domain distorted using the blending functions of Eq. (2), where the four edges of the mapped physical domain are described with the NURBS curves adopted in Ref. [1]. The lamination scheme is the same as the previous example, while the boundary conditions are FCFF, meaning that the edge associated with $\xi_1 = \xi_1^0$ in the parent domain is clamped, whereas the remaining edges are free. The first ten natural frequencies are reported in Table 2 for various higher-order theories. The reference solution is obtained from a 3D FEM model developed with commercial software, made of C3D20 parabolic brick elements and 720756 DOFs. Also in this case, the results demonstrate that the refined 2D theory accurately predicts the response of the reference solution, while requiring significantly less computational effort. The accuracy is particularly evident in those simulations that consider higher-order thickness functions and the zigzag function. Finally, the first nine mode shapes, obtained from the EDZ4 simulation, are presented in Fig. 6.

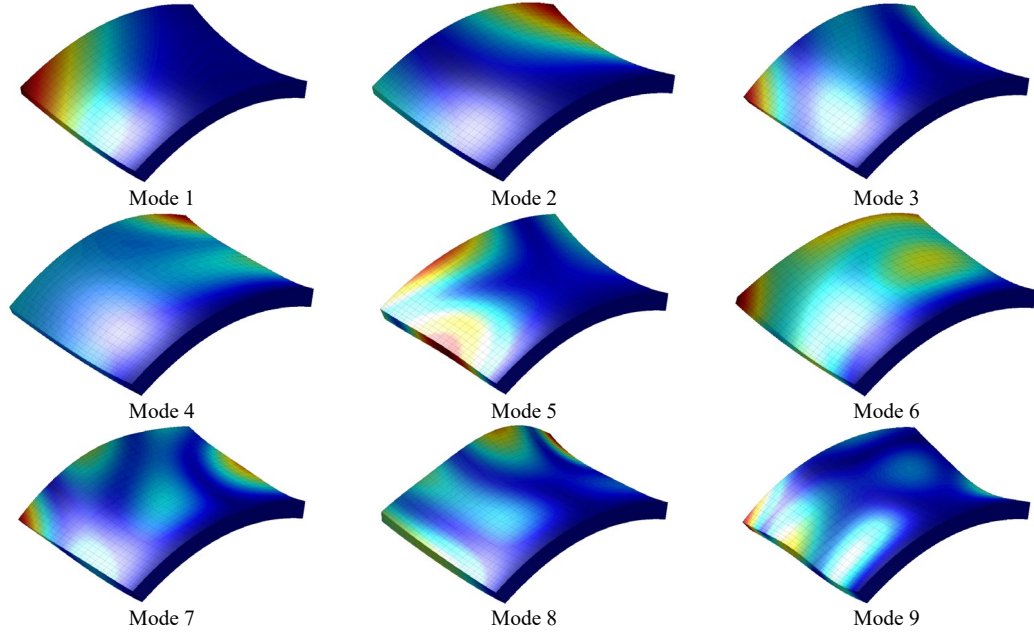


Figure 5. Three-dimensional representation of the first nine mode shapes of a laminated anisotropic hyperbolic paraboloid described with principal coordinates.

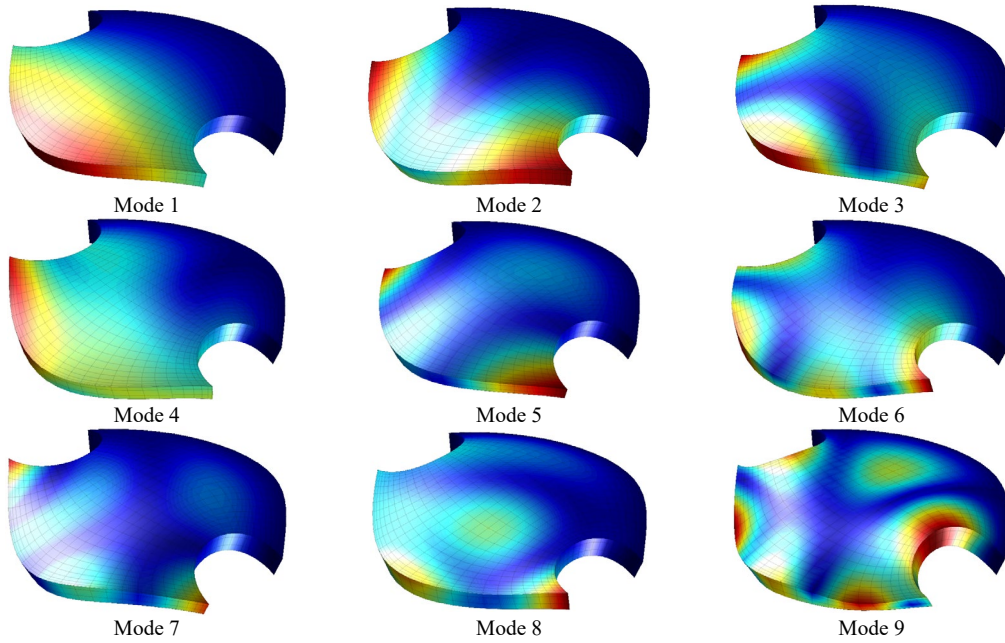


Figure 6. Three-dimensional representation of the first nine mode shapes of a laminated anisotropic elliptic paraboloid described with arbitrarily-shaped domains.

Conclusions. A higher-order ESL model has been presented for the static and dynamic analysis of anisotropic doubly-curved shell structures with arbitrary three-dimensional variations in the material orientation. The formulation is based on a generalized expansion of the unknown field variables, considering both through-the-thickness stretching and zigzag effects between adjacent laminae. The governing equations are derived from the Hamilton principle and solved numerically using the GDQ method. The theory has been successfully applied to predict the static response and natural frequencies of both flat and curved laminated panels with various lamination schemes, showing high accuracy compared to computationally expensive simulations. Moreover, it is shown that this model facilitates the analysis of complex structures that would otherwise require advanced modelling skills when using standard commercial software.

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Table 1. First ten natural frequencies of a hyperbolic paraboloid described in curvilinear principal coordinates employing higher-order theories. Effect of the kinematic model on the accuracy of the solution.

f [Hz]	3D FEM	FSDT	TSDT	EDZ1	ED2	EDZ2	ED3	EDZ3	ED4	EDZ4
DOFs	470856	5046	10092	7569	7569	10092	10092	12615	12615	15138
1	77.20	77.07	77.13	81.35	77.28	77.22	77.49	77.38	77.44	77.33
2	105.91	105.94	106.06	107.68	106.04	105.96	106.35	106.15	106.29	106.09
3	271.14	271.39	271.42	287.17	271.36	271.04	272.41	271.80	272.21	271.54
4	351.81	351.87	352.85	359.09	352.15	351.60	354.23	353.00	354.00	352.58
5	371.33	372.13	372.64	378.77	371.58	371.07	373.12	372.14	372.89	371.77
6	464.62	465.23	465.85	474.82	464.95	464.55	466.38	465.49	466.18	465.18
7	523.07	524.43	526.27	549.22	523.19	522.47	526.93	524.84	526.46	524.35
8	637.18	643.55	644.08	659.28	637.91	636.41	644.17	639.74	642.74	639.20
9	769.22	770.81	774.28	805.51	768.23	766.31	776.65	772.65	775.87	770.74
10	812.01	814.07	818.33	854.03	811.14	809.55	819.98	815.09	818.88	814.05

Table 2. First ten natural frequencies of an elliptic paraboloid of arbitrary shape employing higher-order theories. Effect of the kinematic model on the accuracy of the solution.

f [Hz]	3D FEM	FSDT	TSDT	EDZ1	ED2	EDZ2	ED3	EDZ3	ED4	EDZ4
DOFs	720756	5046	10092	7569	7569	10092	10092	12615	12615	15138
1	68.95	69.40	69.36	71.17	69.30	69.22	69.53	69.36	69.47	69.32
2	142.37	143.03	143.26	145.98	142.40	142.21	143.67	142.89	143.49	142.86
3	321.60	325.31	325.48	330.90	322.59	321.99	325.66	323.59	325.01	323.49
4	395.48	397.32	398.09	410.07	396.61	396.02	399.60	397.63	398.97	397.60
5	486.92	490.53	490.64	502.73	488.19	487.44	491.76	489.38	490.97	489.10
6	644.87	649.16	649.58	665.85	645.89	644.92	650.70	647.47	649.72	646.67
7	811.44	820.12	821.09	847.21	812.22	810.61	820.89	815.87	819.34	814.71
8	852.97	859.66	862.08	882.93	854.22	852.19	863.90	857.32	862.00	856.91
9	989.03	995.68	998.63	1034.67	987.69	985.59	999.17	992.69	997.29	991.41
10	1062.61	1066.56	1066.40	1080.32	1064.68	1063.81	1067.82	1065.37	1066.88	1064.84

Received: 01/09/2025 Accepted: 11/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-17-23>

STABILITY OF FUNCTIONALLY GRADED CYLINDERS UNDER HYDROSTATIC PRESSURE WITH FIXED BOUNDARY CONDITIONS RESTING ON ELASTIC FOUNDATIONS

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Abstract. In this study, the buckling problem of cylindrical shells composed of functionally graded materials (FGMs) under hydrostatic pressure and resting on a Pasternak-type elastic foundation is investigated. First, the fundamental relations of functionally graded (FG) cylindrical shells and the Pasternak elastic foundation model are mathematically formulated, and then the governing equations are derived. By seeking appropriate shape functions satisfying fixed boundary conditions, the Galerkin procedure is applied to solve the resulting partial differential equations. An analytical expression for the dimensionless critical hydrostatic pressure (DCHP) of FG cylindrical shells with fixed edges on a Pasternak elastic foundation is obtained. This expression is minimized with respect to the buckling mode, and the minimum values of DCHP are calculated numerically both in the presence and absence of the elastic foundation. Considering different volume fraction indices and foundation parameters, the minimum values of DCHP are determined, followed by numerical analyses, interpretations, and generalizations.

Keywords: functionally graded material, fixed boundary conditions, cylindrical shells, stability, critical hydrostatic pressure, elastic foundations

1. Introduction. Composite materials have long attracted significant interest from researchers due to their superior properties such as low weight, high strength, and resistance to corrosion and wear. Owing to these advantages, they are widely used across a range of engineering applications. However, one of the main drawbacks of traditional composite materials is the occurrence of sudden changes in mechanical properties at the interfaces between different constituents, which can lead to crack initiation and propagation. To address this issue, a new class of composite materials known as Functionally Graded Materials (FGMs) was introduced by Japanese material scientists in 1984 as part of a space research project. FGMs enable a smooth and continuous variation of physical, chemical, and mechanical properties—such as elastic modulus, Poisson's ratio, and density—across the material volume [1].

In the literature, two principal modeling approaches are commonly employed to represent FGMs. In the first approach, the volume fraction of the ceramic or metallic phase is assumed to be a piecewise continuous function. Accordingly, the FGM structure is modeled as a series of sub-layers, each with constant volume fractions, effectively treating the material as composed of semi-homogeneous ceramic-metal layers. In this way, material properties remain uniform within each layer while transitioning gradually between layers, enabling a simplified yet practical modeling framework for engineering analyses.

In contrast, the second approach assumes a continuously varying volume fraction of the constituent phases across the thickness of the structure, resulting in a more realistic representation of material heterogeneity. In this method, the ceramic volume fraction is defined as a continuous function

of the through-thickness coordinate, allowing the modeling of FGMs with a smooth gradation profile instead of discrete layers [2, 3].

FGMs have demonstrated considerable potential in various engineering domains, and interest in their mechanical behavior and potential applications continues to grow [4]. The advantages of FGMs necessitate thorough investigations into the structural responses of FGM-based components under different elastic foundations, loading conditions, and boundary constraints, and integrating these responses into engineering design practices. In this context, a substantial body of research has been dedicated to the stability and vibration analysis of cylindrical shells composed of FGMs [5–9].

However, most existing studies have focused on simply supported boundary conditions without considering the influence of the elastic foundation, relying primarily on analytical or numerical methods. In many advanced industrial applications, FGM cylindrical shells are embedded within elastic media, where the foundation effect plays a non-negligible role in their structural behavior. These surrounding media can be effectively modeled using various parameters, among which the two-parameter Pasternak foundation model is frequently employed due to its ability to account for both shear interaction and normal stiffness [10].

In recent years, growing attention has been directed towards the stability behavior of fixed FGM cylindrical shells under external pressure while embedded in elastic media [11–13]. Such structures are widely used in advanced engineering applications including aerospace and aeronautical engineering, nuclear energy systems, biomedical implants, automotive industry, and thermal protection systems. Accurate modeling of their stability behavior under fixed boundary conditions and external pressure is crucial for ensuring structural safety, longevity, and performance. Furthermore, the inclusion of elastic foundation effects enables more realistic designs for systems involving soil-structure interaction, embedded structures, and elastomer-supported configurations.

A review of the current literature reveals that analytical studies addressing the buckling behavior of fixed FGM cylindrical shells under hydrostatic pressure in an elastic medium are still relatively limited. This study aims to address this research gap and contribute to the growing body of knowledge in the field. In addition, it provides a theoretical modeling framework that can serve as a foundation for the development of design criteria applicable to various engineering disciplines.

2. Formulation of the problem. In this study, a functionally graded cylindrical shell characterized by thickness t , radius r , and length a is examined under the assumption that it is supported by a Pasternak-type elastic foundation, as schematically illustrated in Fig. 1. A Cartesian coordinate system $Oxyz$ is introduced such that the origin OOO coincides with the left boundary of the shell's mid-surface. The Oxx -axis is directed along the shell's longitudinal axis, whereas the Oy -axis follows the circumferential direction. The Oz -axis is defined as the outward normal to the mid-surface generated by the Ox – Oy plane, oriented radially inward toward the geometric center of the cylindrical configuration. This coordinate convention permits a systematic representation of both the kinematic field and the associated deformation measures.

The elastic foundation considered in this work incorporates the Pasternak formulation, which accounts for both normal Winkler-type resistance and the shear interaction between adjacent foundation springs. Within this analytical framework, the governing expression of the Pasternak foundation response is introduced in the following form [9]:

$$R = k_1 w - k_2 \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) \quad (1)$$

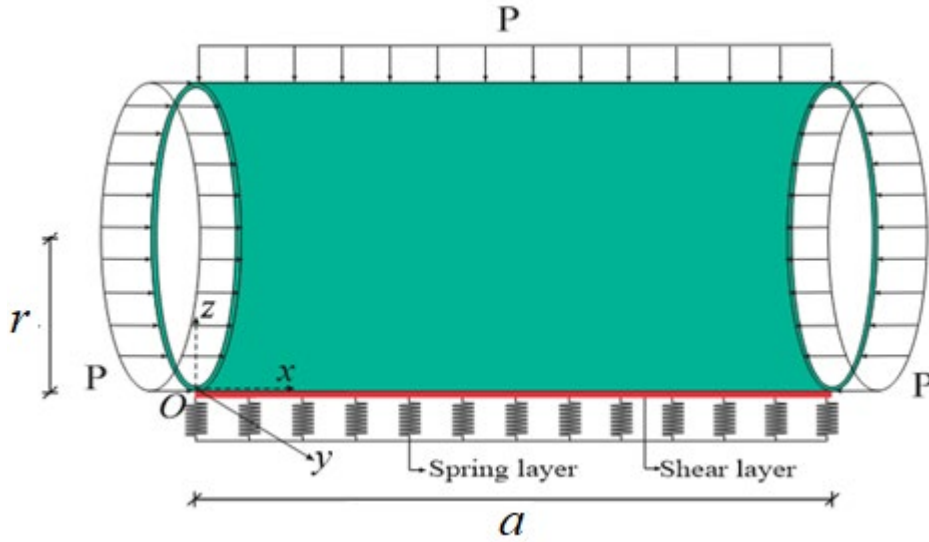


Fig. 1. FG cylindrical shell resting on a Pasternak elastic foundation under hydrostatic pressure and the associated coordinate system

In this formulation, R denotes the distributed reaction generated by the Pasternak–Winkler elastic substrate. The parameter k_1 (N/m³) corresponds to the classical Winkler modulus, representing the compressive stiffness of the foundation in the transverse direction, whereas k_2 (N/m) characterizes the shear stiffness associated with an idealized, exceedingly thin intermediate layer that permits shear interaction between adjacent foundation points. The quantity w signifies the transverse displacement of the shell mid-surface, assumed to remain small compared with the shell thickness and measured normal to the reference surface. Collectively, this two-parameter foundation model captures the combined influence of vertical resistance and shear coupling, thereby providing a more realistic representation of the substrate response than the Winkler model alone.

Functionally graded materials are commonly characterized through either power-law or exponential gradation schemes. In the present analysis, the cylindrical shell is assumed to follow a power-law variation in its material composition. Accordingly, the equivalent elastic parameters of the shell—specifically the effective Young’s modulus and Poisson’s ratio—are formulated as given below [11]:

$$E_z^{fg} = \left(\frac{2z+t}{2t} \right)^N (E_c - E_m) + E_m, \quad \nu_z^{fg} = \left(\frac{2z+t}{2t} \right)^N (\nu_c - \nu_m) + \nu_m \quad (2)$$

Assuming that the functionally graded cylindrical shell is subjected to a spatially uniform hydrostatic load, the corresponding membrane force relations—formulated without invoking the first moment of stresses about the reference surface—can be expressed in the following form:

$$N_{11}^0 = -0.5 \cdot r \cdot P, \quad N_{12}^0 = 0, \quad N_{22}^0 = -r \cdot P \quad (3)$$

3. Governing equations and solution procedure. The governing equations for cylindrical shells made of FGMs can be expressed within the framework of the Kirchhoff–Love shell theory can be obtained as follows [8]:

$$S_1 \frac{\partial^4 \Psi}{\partial x^4} + 2(S_2 - S_5) \frac{\partial^4 \Psi}{\partial x^2 \partial y^2} + S_1 \frac{\partial^4 \Psi}{\partial y^4} + \frac{1}{r} \frac{\partial^2 \Psi}{\partial x^2} - S_3 \frac{\partial^4 w}{\partial x^4} - 2(S_4 + S_6) \frac{\partial^4 w}{\partial x^2 \partial y^2} - S_3 \frac{\partial^4 w}{\partial y^4} + \frac{1}{r} \frac{\partial^2 w}{\partial x^2} - 0.5r \cdot P \frac{\partial^2 w}{\partial x^2} - r \cdot P \frac{\partial^2 w}{\partial y^2} - k_1 w + k_2 \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) = 0 \quad (4)$$

$$T_1 \frac{\partial^4 \Psi}{\partial x^4} + 2(T_2 + T_5) \frac{\partial^4 \Psi}{\partial x^2 \partial y^2} + T_1 \frac{\partial^4 \Psi}{\partial y^4} - T_4 \frac{\partial^4 w}{\partial x^4} - 2(T_3 - T_6) \frac{\partial^4 w}{\partial x^2 \partial y^2} - T_{14} \frac{\partial^4 w}{\partial y^4} + \frac{1}{r} \frac{\partial^2 w}{\partial x^2} = 0 \quad (5)$$

In this context, the coefficients $S_k, T_k (k=1,2,...,6)$ are parameters determined by the material gradation characteristics of the FGM and the geometric and mechanical properties of the cylindrical shell.

At both longitudinal ends of the FG cylindrical shell, fixed boundary conditions are assumed to be valid [3, 8, 13]. The following approximating functions, corresponding to the deflection and the Airy stress function, are constructed to satisfy the fixed boundary conditions [8]:

$$w = C_1 \sin^2 \alpha_1 x \cos \alpha_2 y, \quad \Psi = C_2 \sin^2 \alpha_1 x \cos \alpha_2 y \quad (6)$$

Here, $\alpha_1 = \frac{m\pi}{a}$ and $\alpha_2 = \frac{n\pi}{r}$ are parameters, while m and n denote the longitudinal and circumferential wave numbers, respectively. The coefficients $C_j (j=1,2)$ represent the unknown amplitudes associated with the deflection and the Airy stress function.

For FG cylindrical shells resting on a Pasternak foundation and subjected to hydrostatic pressure, the strain compatibility and stability equations defined by (6) and (7) are multiplied by a weight function over the relevant region $\Lambda = \{(x, y) : 0 \leq x \leq a, 0 \leq y \leq 2\pi r\}$, and the Galerkin procedure is applied. As a result of this process, the following analytical expression is obtained for the critical hydrostatic pressure of the fixed FG cylindrical shells:

$$P_{wp}^{Hcr} = \frac{1}{(2\alpha_1^2 + 3\alpha_2^2)r} \left\{ 16C_3\alpha_1^4 + 8\alpha_1^2\alpha_2^2(C_4 + C_6) + 3C_3\alpha_2^2 - \right. \\ \left. - \left[16C_2\alpha_1^4 + 8\alpha_1^2\alpha_2^2(C_1 - C_5) + 3C_2\alpha_2^4 - \frac{4\alpha_1^2}{r} \right] \right. \\ \left. \times \frac{16B_4\alpha_1^4 + 4\alpha_1^2\alpha_2^2(2B_3 - B_6) + 3B_4\alpha_2^4 + \frac{4\alpha_1^2}{r}}{16B_1\alpha_1^4 + 8\alpha_1^2\alpha_2^2(2B_2 + B_5) + 3B_1\alpha_2^4} + 3k_1 + k_2(4\alpha_1^2 + 3\alpha_2^2) \right\} = 0 \quad (7)$$

The expression given below is employed for evaluating the DCHP of FG cylindrical shells with both ends fixed and supported by a Pasternak elastic foundation:

$$P_{1wp}^{Hcr} = \frac{P_{wp}^{Hcr}}{E_c} \quad (8)$$

Equation (7) yields a particular case representing the critical hydrostatic pressure for EG cylindrical shells without foundation support when the foundation parameters k_1 and k_2 are set to zero.

Minimization of equation (7) with respect to the mode pairs (m, n) yields the minimum values of the DCHP. For the numerical computation of these values, the Maple software is utilized.

4. Results and discussions. In numerical analyses, two different types of cylindrical shells with distinct FG profiles, denoted as FG₁ and FG₂, are considered. These functionally graded materials are composed of mixtures of metal and ceramic phases. Specifically, the cylindrical shell composed of Si₃N₄ (silicon nitride) and SUS304 stainless steel is referred to as FG₁, while the shell formed from Ti-6Al-4V titanium alloy and ZrO₂ (zirconia) is referred to as FG₂. The mechanical properties of these materials and their constituent components are adopted from the study by Shen [13]. The geometric parameters of the cylindrical shell are taken as follows: $r/t=75$ ve $a/r=2$.

Table 1 presents the variation of the DCHP values for the FG₁-quad and FG₂-quad profiles as a function of the elastic foundation parameters k_1 and k_2 . When comparing DCHP values of cylindrical shells with FG₁-quad and FG₂-quad profiles to those of homogeneous Si₃N₄ and ZrO₂ cylindrical shells, it is observed that in the absence of a foundation, the FG₁ and FG₂ profiles enhance the DCHP capacity by approximately +19.6% and +24%, respectively. However, this enhancement effect

generally diminishes as the foundation parameters k_1 and k_2 increase. For instance, when $k_2 = 0$ and k_1 increases from 1×10^6 to 3×10^6 , the influence of the FG₂ profile on the DCHP compared to the ZrO₂ shell decreases from 23.8% to 23.3%. Similarly, the effect of the FG₁ profile compared to the Si₃N₄ shell reduces from 19.6% to 19.3%. Similarly, when $k_1 = 1 \times 10^6$ and k_2 increases from 5×10^4 to 7×10^4 , the contribution of the FG₂ profile to the DCHP, compared to the ZrO₂ cylindrical shell, decreases from 22.9% to 22.6%, while that of the FG₁ profile, compared to the Si₃N₄ shell, reduces from 19.1% to 19%. Moreover, when $k_1 = 2 \times 10^6$ and k_2 increases from 5×10^4 to 7×10^4 , the enhancement effect of the FG₂ scheme drops from 22.6% to 22.4%, whereas the enhancement provided by the FG₁ profile decreases from 19% to 18.9%, relative to the corresponding homogeneous ceramic shells. Finally, for $k_1 = 3 \times 10^6$ and an increase in k_2 from 5×10^4 to 7×10^4 , the DCHP improvement of the FG₂ profile declines from 22.5% to 22.2%, and that of the FG₁ profile decreases from 19% to 18.8%.

Table 1. Variation of the DCHP values with respect to k_1 and k_2 for cylindrical shells made of Si₃N₄, FG₁, SUS304, ZrO₂, FG₂, and Ti-6Al-4V

$P_{1wp}^{Hcr} \times 10^5 (n_{cr}) (n)$							
k_1	k_2	Si ₃ N ₄	FG ₁ -quad	SUS304	ZrO ₂	FG ₂ -quad	Ti-6Al-4V
0	0	1.116 (6)	0.897 (6)	0.747 (6)	1.146 (6)	0.871 (6)	0.721 (6)
1×10^6	0	1.123 (6)	0.903 (6)	0.753 (6)	1.158 (6)	0.883 (6)	0.733 (6)
	5×10^4	1.144 (6)	0.925 (6)	0.775 (6)	1.2 (6)	0.925 (6)	0.774 (6)
	7×10^4	1.153 (6)	0.934 (6)	0.783 (6)	1.216 (6)	0.941 (6)	0.791 (6)
2×10^6	0	1.129 (6)	0.91 (6)	0.76 (6)	1.17 (6)	0.895 (6)	0.745 (6)
	5×10^4	1.15 (6)	0.931 (6)	0.781 (6)	1.211 (6)	0.937 (6)	0.786 (6)
	7×10^4	1.159 (6)	0.94 (6)	0.79 (6)	1.228 (6)	0.953 (6)	0.803 (6)
3×10^6	0	1.135 (6)	0.916 (6)	0.766 (6)	1.182 (6)	0.907 (6)	0.756 (6)
	5×10^4	1.157 (6)	0.937 (6)	0.787 (6)	1.223 (6)	0.948 (6)	0.798 (6)
	7×10^4	1.165 (6)	0.946 (6)	0.796 (6)	1.24 (6)	0.965 (6)	0.814 (6)

When comparing the critical hydrostatic pressure values of cylindrical shells with FG₁ and FG₂ profiles to those of homogeneous Ti-6Al-4V and SUS304 shells, respectively, it is observed that, in the absence of a foundation, the FG₁ and FG₂ profiles result in reductions of approximately (-20.8%) and (-20.1%), respectively. This reduction effect generally weakens as the foundation stiffness parameters k_1 and k_2 increase. For example, when $k_2 = 0$ and k_1 increases from 1×10^6 to 3×10^6 , the reduction in the critical hydrostatic pressure for the FG₂ profile (compared to the Ti-6Al-4V shell) decreases from (-20.5%) to (-20%), while for the FG₁ profile (compared to the SUS304 shell), it decreases from (-19.9%) to (-19.6%).

Similarly, when $k_1 = 1 \times 10^6$ and k_2 increases from 5×10^4 to 7×10^4 , the reduction in critical hydrostatic pressure for the FG₂ model decreases from (-19.5%) to (-19%), and for the FG₁ profile from (-19.4%) to (-19.3%), in comparison to their corresponding homogeneous metallic shells. Moreover, when $k_1 = 2 \times 10^6$ and k_2 increases from 5×10^4 to 7×10^4 , the FG₂ scheme's reduction effect decreases from (-19.2%) to (-19%), while that of the FG₁ profile decreases from (-19.2%) to (-18.7%). Finally, for $k_1 = 3 \times 10^6$ and as k_2 increases from 5×10^4 to 7×10^4 , the critical hydrostatic

pressure reduction for the FG₂ profile declines from (–16.5%) to (–16.1%), and for the FG₁ profile from (–19.1%) to (–18.8%), compared to Ti-6Al-4V and SUS304 shells, respectively.

Fig. 2 presents the variation of the DCHP as a function of the material grading index N for cylindrical shells with FG₁ and FG₂ profiles, both with and without elastic foundation support. The geometric parameters are taken as $r/t=100$ ve $a/r=2$, while the foundation stiffness coefficients are selected as $k_1=k_2=0$, $k_1=2\times 10^6, k_2=0$, and $k_1=2\times 10^6, k_2=5\times 10^4$. It is observed that increasing the value of N leads to a decrease in DCHP values for both FG₁ and FG₂ profiles. When comparing the FG₁ and FG₂ profiles, the minimum DCHP values occur at $N=3$, while the maximum values are obtained at $N=0.5$. The most pronounced influence of the Pasternak foundation occurs in the FG₂ shell with $N=2$, where the effect reaches 7.6%. In contrast, the weakest foundation influence is observed in the presence of the Winkler foundation, yielding only 1.2% for the FG₁ shell with $N=0.5$. The increase in the power-law index N leads to a regular and pronounced enhancement in the influence of the Pasternak foundation on the critical hydrostatic load, particularly for $N \leq 2$. Although the effect continues to grow beyond $N=2$, the rate of increase becomes noticeably weaker. In contrast, the influence of the Winkler foundation, while generally increasing, exhibits an irregular pattern and does not follow a consistent trend. As the N exponent increases from 0.5 to 3, the FGM effect on DCHP increases.

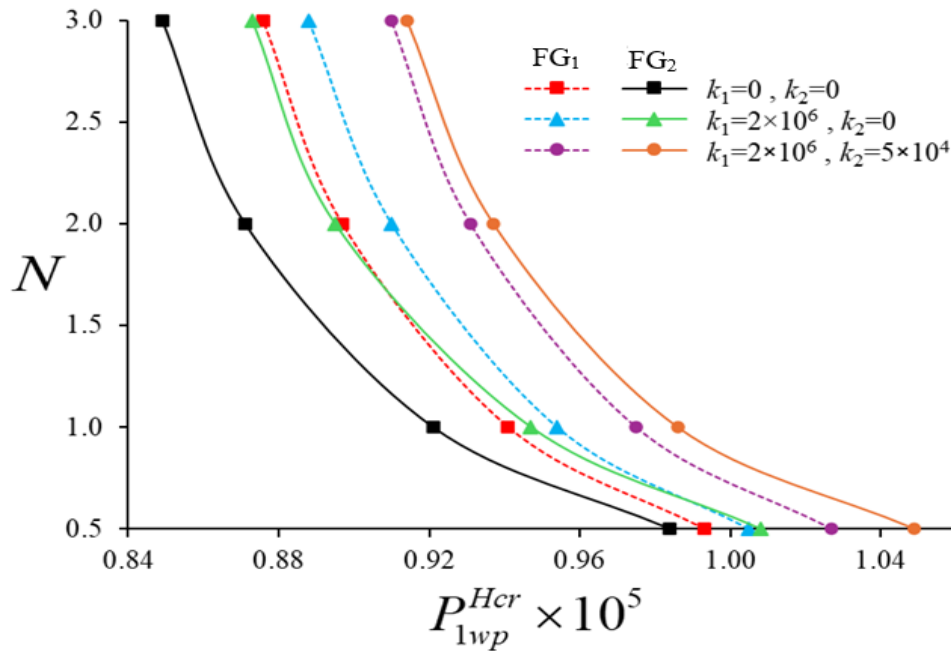


Fig. 2. Variation of the DCHP with respect to the material grading index N for cylindrical shells with FG₁ and FG₂ profiles, with and without elastic foundation support

5. Conclusions. In this investigation, the stability behavior of functionally graded cylindrical shells subjected to external hydrostatic loading is examined within the framework of Donnell-type shell theory resting on an elastic foundation. The study first formulates the governing relations describing the material gradation, elastic foundation response, and hydrostatic loading in a unified mathematical setting. Thereafter, employing a combined Pasternak–Winkler foundation model, the corresponding stability and compatibility equations are rigorously derived based on the classical Kirchhoff–Love shell assumptions. To facilitate an analytical treatment, admissible mode shapes satisfying fixed–fixed boundary conditions are introduced, and closed-form solutions are obtained through the application of the Galerkin procedure. A comprehensive parametric study is then carried out by varying the material distribution and foundation stiffness parameters in order to quantify their individual and combined effects. The results of the numerical investigation yield several overarching conclusions:

- a) The FG₂ gradation consistently provides enhanced stability characteristics, particularly under conditions involving large foundation stiffness.
- b) Although the FG₁ profile exhibits a comparatively steeper reduction in critical load when the foundation stiffness is negligible or small, the presence of an elastic foundation significantly narrows this performance gap.
- c) For design scenarios where high stability margins are essential, the FG₂ configuration and ceramic-rich compositions are recommended, whereas the FG₁ profile offers advantages in applications prioritizing reduced weight alongside moderate stability requirements.

Collectively, these findings underscore that an informed selection of material gradation patterns and foundation parameters plays a decisive role in the development of next-generation structural components, enabling designers to achieve an optimal balance among mechanical robustness, lightweight performance, and application-specific functional criteria.

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Received: 07/09/2025 Accepted: 16/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-24-38>

A SHORT SURVEY OF THE THERMOPHYSICAL CHARACTERISTICS OF THE HYBRID NANOFLUIDS

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Abstract. Nanofluids (NFs) are suspensions of nanoparticles in a fluid with improved characteristics at low concentrations, gaining importance in various technical sectors like automotive, healthcare, power plant cooling systems, and computing equipment. Better heat transfer capacities, thermal conductivities, and stability can be counted among the advantages that NFs can provide. Whereas nanoparticle addition may also raise viscosity, albeit increasing thermal conductivity, curbing their thermal advantages. Stability and temperature behavior are crucial issues. Hybrid nanofluids (HNFs) are highly sought after due to their superior thermophysical properties compared to conventional base fluids. To produce these high-performance heat transfer fluids, two or more different nanoparticles are suspended in a base fluid. By highlighting their remarkable characteristics and uses, this research reveals the great potential of HNFs, especially in thermal operations. Binary and ternary thermophysical properties, including heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, heat transfer efficiency, zeta potential, stability, thermal efficiency, isobaric heat capacity, and specific heat capacity, have been used to categorize the literature. In addition, the present work scrutinizes studies related to HNFs, particularly those focused on thermal conductivity and viscosity, and covers ingredients such as nanoparticle type, concentration, temperature, and surfactant use for the purpose of preventing sedimentation and agglomeration. Moreover, the paper delivers an improved investigation on NFs' properties, especially involving their physical and rheological aspects in the context of heat transfer enhancement.

Keywords: nanofluids, hybrid nanofluids, heat conductivity, viscosity, rheology

1.Introduction. The rapid technological advancements in today's technology era have led to a need for heat transfer enhancement in the thermal industry. Conventional single-phase fluids are used in real-time heat exchange units, but they struggle to enhance heat transfer coefficient and performance. Researchers have discovered the employment of high thermal conductive fluids, such as NFs, as a promising alternative. NFs are colloidal suspensions at the nanoscale in base fluids like ethylene glycol, ethanol, and water, which facilitate Brownian agitation and increase heat transfer rate. This approach is considered a promising alternative to conventional single-phase fluids. Fig. 1 presents a classification of research trends in HNFs, focusing on thermophysical parameters and HNF types. The figure has three core attention areas as follows: thermal conductivity, dynamic viscosity, and concurrent examinations. Each ingredient's subdivisions distinguish between a binary HNF and a ternary HNF also emphasizing the complication and invention of the NFs being researched. This distinction is crucial in understanding the intricacies of HNF research.

The primary advantage of HNFs is their excellent thermal conductivity and heat transfer

characteristics, which enhance heat transfer efficiency, as highlighted in Figure 2. Conventional NFs have established technology and simplified formulation, indicating maturity, production efficiency, and cost reduction. HNFs offer superior heat transfer capabilities, making them useful in various applications, especially energy storage systems. The usefulness of HNFs can be enhanced through optimizing their characteristics and efficiency.

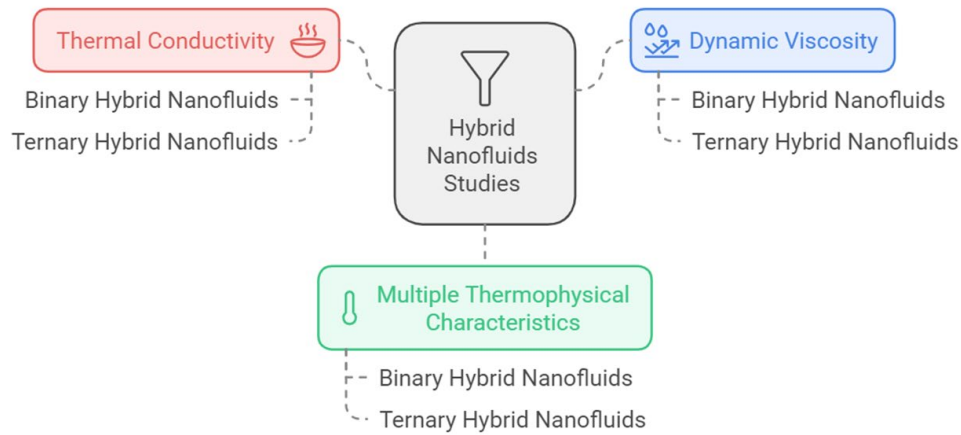


Fig. 1. Sections of the presentation

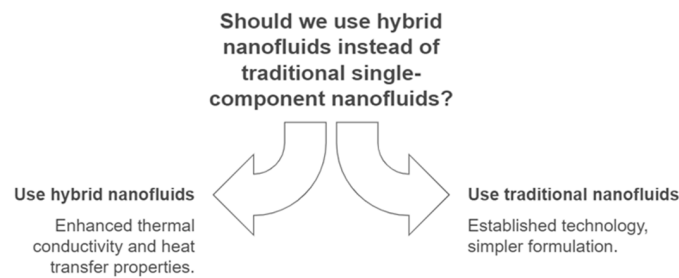


Fig. 2. Main questions about hybrid nanofluids in thermal systems

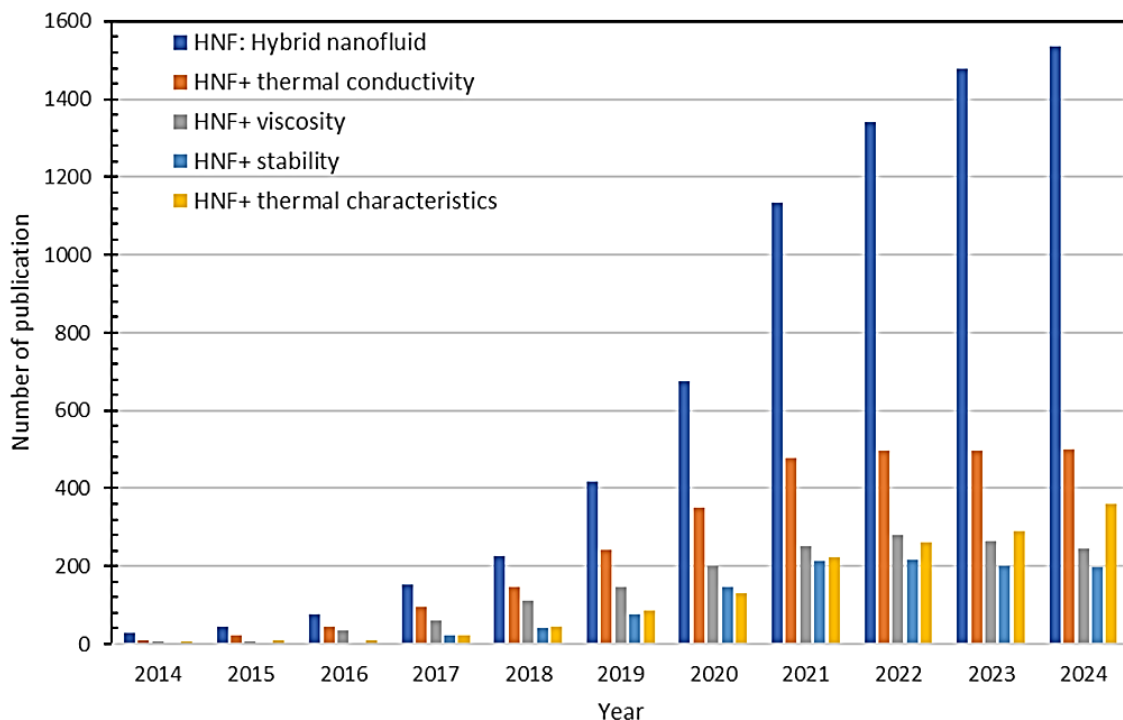


Fig. 3. Number of publications on hybrid NFs by year in WOS database

Even though the studies on NFs were initiated more than three decades, it gained momentum only in the last decade, as shown in Fig. 3. Opportunities and obstacles of NFs in thermal applications are summarized in Table 1. Although NFs hold significant potential for heat transfer applications, their stability issues, which can substantially influence performance, must be carefully addressed.

Table 1. Potential benefits and limitations of nanofluids in thermal applications

Opportunities	Obstacles
Enhanced heat transfer	Complex formulation
Energy storage benefits	Stability issues
Optimizable performance	Cost of nanoparticles
Versatile application	Compatibility concerns
	Potential environmental and recycling issue

Fig. 4 reveals the connection between these categories and efficiency in heat transfer, thus pointing out the advantages of using HNFs for advancing thermal control. The investigation delivers thorough information on HNFs and their promising aspects. The paper highlights the significance of enhancing viscosity and increasing thermal conductivity, which can also be seen as the core topic of most studies. In addition to these, such factors as viscosity, stability, and general thermal characteristics have also acquired interest. These novel research directions also enable perceptive analysis of HNF production and point out the present issues by carrying out proposed improvements and thus dependability, efficiency, and clarity of HNFs in many fronts of industrial processes.

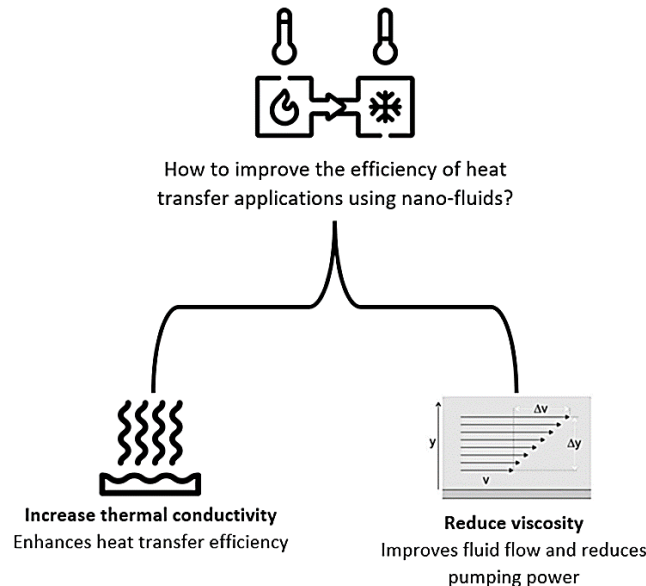


Fig. 4. The efficiency aspect in heat transfer applications with respect to thermal conductivity and viscosity

2.Arrangement of nanofluids. The literature consists of two fundamental techniques: one-step and two-step methods. The one-step method offers long-term stability and a homogeneous structure but is complex and costly. The two-step method, nevertheless, has disadvantages like sedimentation and homogenization requirements. Sedimentation can occur through either method, depending on the reagents and procedures used [2]. Despite these, the two-step method is often preferred due to its cost,

preparation, and practicality [3]. This method was used in this study to formulate NFs.

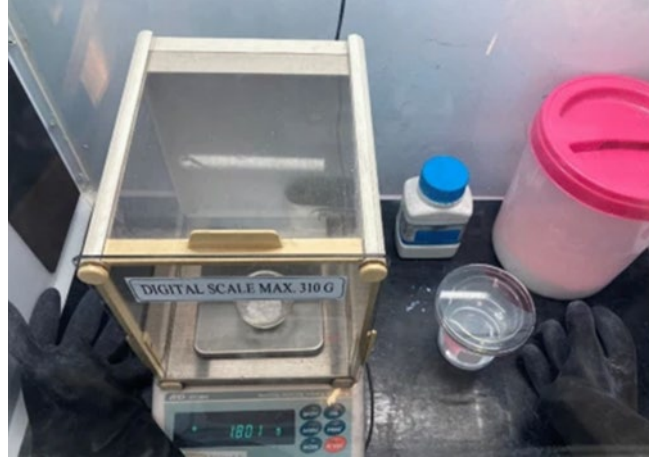


Fig. 5. A typical digital scale

The studies use a digital scale, as shown in Figure 5, to weigh nanoparticles and base fluid, determining the required amounts for different nanofluids. In this figure, the A&D Weighing GF-300 Digital Balance is seen measuring the masses of each substance. The procedure is conducted within an enclosure set up to make up nanofluids. Figure 5 depicts this arrangement and digital balance. For example, to create 1, 2, and 3% NFs, 2.116 g, 4.275 g, and 6.478 g of nanoparticles were needed in 100 g of an ethylene-water-based fluid. The volumetric fraction of nanoparticles was found by Eq. 1, which can be employed in NF and HNF investigations to calculate volumetric concentrations.

$$\phi = \frac{\left(\frac{m_{\text{SiO}_2}}{\rho_{\text{SiO}_2}}\right)}{\left(\frac{m_{\text{SiO}_2}}{\rho_{\text{SiO}_2}}\right) + \left(\frac{m_{\text{EG-w}}}{\rho_{\text{EG-w}}}\right)} \times 100 \quad (1)$$

$$\phi = \frac{\left[\frac{m_{\text{np1}}}{\rho_{\text{np1}}}\right] + \left[\frac{m_{\text{np2}}}{\rho_{\text{np2}}}\right] + \left[\frac{m_{\text{np3}}}{\rho_{\text{np3}}}\right] + \left[\frac{m_{\text{np4}}}{\rho_{\text{np4}}}\right]}{\left[\frac{m_{\text{np1}}}{\rho_{\text{np1}}}\right] + \left[\frac{m_{\text{np2}}}{\rho_{\text{np2}}}\right] + \left[\frac{m_{\text{np3}}}{\rho_{\text{np3}}}\right] + \left[\frac{m_{\text{np4}}}{\rho_{\text{np4}}}\right] + \left[\frac{m_{\text{bf}}}{\rho_{\text{bf}}}\right]} \times 100$$



Fig. 6. An ultrasonic homogenization apparatus [from Atmaca et al. [4] with permission from Springer]

The studies involve adding weighed nanoparticles and surfactants to a base fluid, which is then blended by means of a homogenizer. For example, the samples are homogenized via a Hielscher UP200Ht for 2 hours as shown in Fig. 6, causing a temperature increase and a change in nanoparticle volumetric fraction. Resulting in a uniform dispersion of nanoparticles has been of enormous significance for stability within the production of nanofluids. For this reason, sonication and surfactants were utilized to overcome this problem by adjusting parameters according to information from literature. To impede the nanofluids' evaporation and to hold the ambient temperature comprise great obstacles. A temperature-controlled bath is employed to adjust the temperature within the sonication process to circumvent this obstacle. The NFs are cooled using a chiller to maintain nanoparticle concentrations.

2.Measurements of nanofluids' thermophysical properties. Since it impacts the thermal properties, stability is of great significance for nanofluids. To acquire homogenous thermal properties at every point of the mixture, maintaining a uniform structure is required. Waiting time, suspension pH, base fluid type, nanoparticle type, diameter, and nanofluid preparation comprise ingredients influencing stability. In this context, the Malvern Zetasizer Nano ZS has been extensively utilized to measure the stability of nanofluids. For sample volumes within the interval of 150-180 μL , the device can measure Zeta potential along a wide range of particle sizes. The nanofluids are sonicated for 20 minutes before measurements, with each measurement taking around 2 minutes. The average value of three measurements is used as the last outcome.

Lee et al. [5] defined excellent stability as a zeta potential value above 60 mV, physical stability between 60 and 30 mV, and limited stability below 20 mV. In Fig. 7, The zeta potential value of 1% ZnO 0.50-SiO₂ 0.50 NF was measured at Yildiz Technical University's Science and Technology Application and Research Center. The zeta potential value is a measure showing that raising it raises thermal conductivity. The sample has a - 14 mV zeta potential value after preparation. 1% ZnO 0.50-SiO₂ 0.50 nanofluid is considered limited stability, even with a 10% gum Arabic surfactant. Factors such as density, ultrasonication time, nanoparticle shape, and high NF concentration may negatively affect stability. After the NFs are made up, around 100 mL are kept for visual observation as shown in Figure 8. The NFs are replaced in cylindrical bottles cleaned with alcohol and dried afterwards. Bottles of NFs are kept airtight at room temperature. All NFs are snapped at 1, 7, 14, and 28 days after creation for the control of sedimentation by visual observation. The outcomes of visual observation are given in Table 2. Fig. 8 illustrates images of hybrid nanofluids as well [4].

Table 2. Durations for which nanofluids showed no sedimentation

Nanofluid/Vol. concentration	0.1%	0.5%	1%
MWCNT	7 days	1–7 days	1–7 days
SiO ₂	> 28 days	> 28 days	> 28 days
ZnO	1–7 days	1–7 days	1–7 days
TiO ₂	> 28 days	1–7 days	1–7 days
SiO ₂ -TiO ₂	> 28 days	–	–
SiO ₂ -TiO ₂ -MWCNT	> 28 days	–	–
SiO ₂ -TiO ₂ -MWCNT-ZnO	1–7 days	–	–

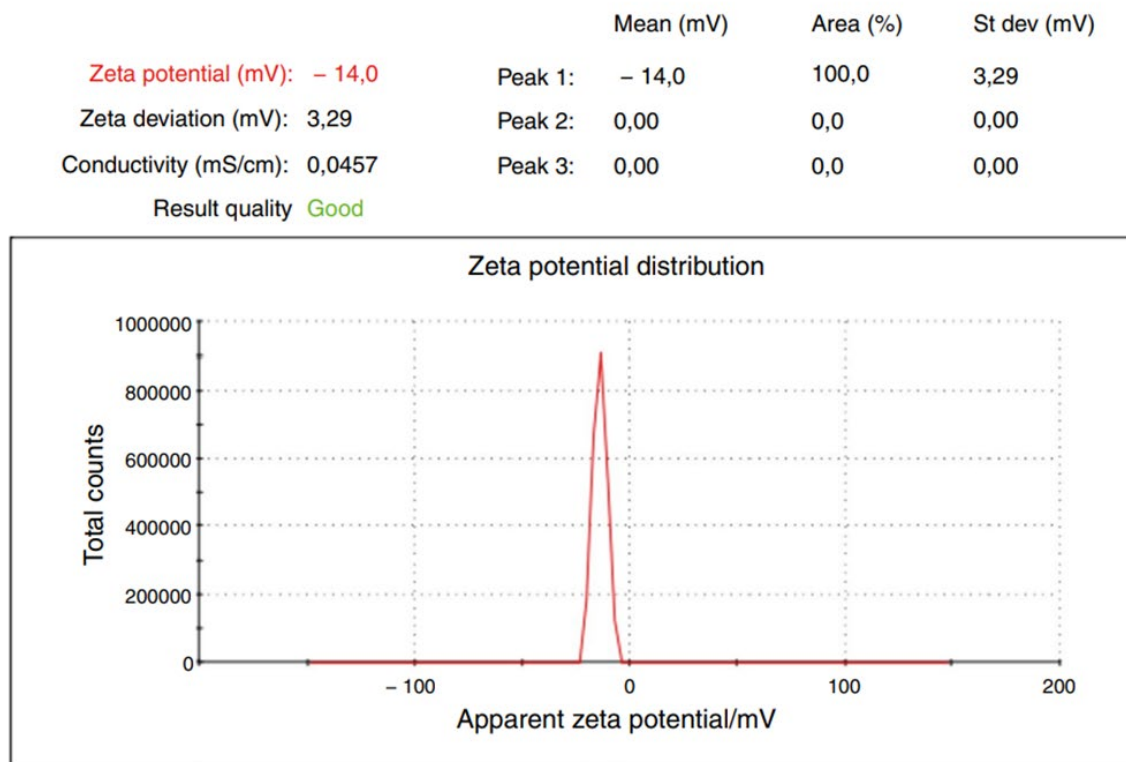


Fig. 7. Zeta potential value of 1% ZnO 0.50-SiO₂ 0.50

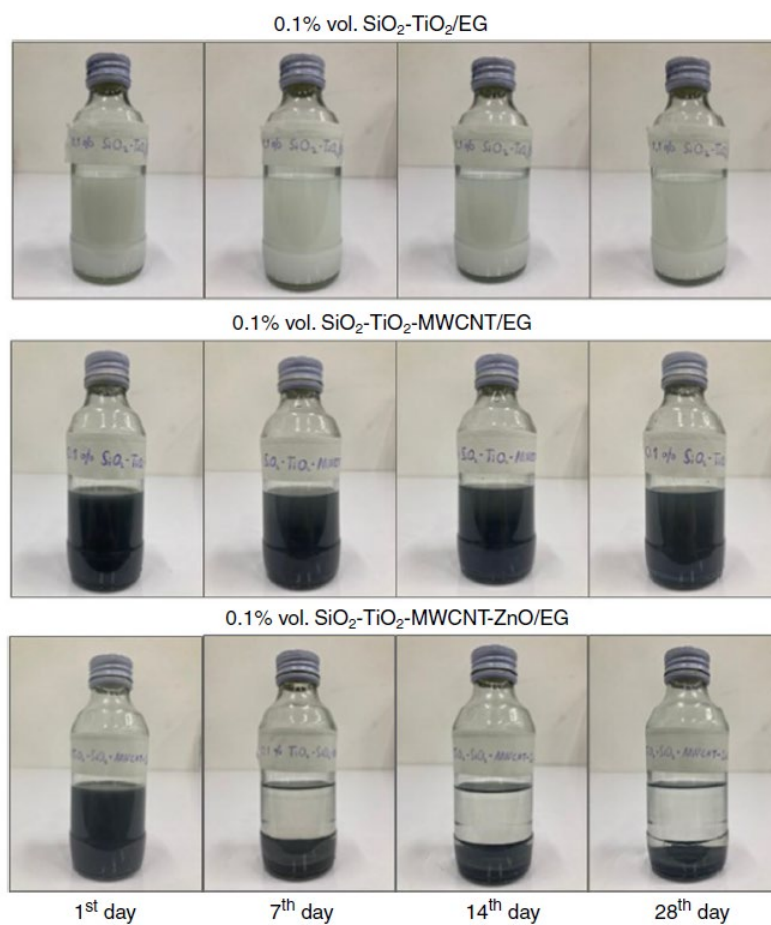


Fig. 8. Visual observation of hybrid nanofluids 1, 7, 14, and 28 days after formulation [from Atmaca et al. [4] with permission from Springer]

These findings in Table 2 have brought literature to the conclusion to produce hybrid nanofluids having a volume concentration of 0.1% to diminish nanoparticle sedimentation. Resembling behavior of SiO₂ and TiO₂ single nanofluids at 0.1% volume concentrations, deterioration was not observed after 28 days for the SiO₂ TiO₂/EG nanofluid. After 28 days, the SiO₂-TiO₂-MWCNT/EG nanofluid has not deteriorated depicting much better stability. The SiO₂-TiO₂-MWCNT-ZnO/EG nanofluid, because of instabilities, has solidified in 7 days. The ZnO nanoparticles were rather great, and the material was dense.

One more analysis method employed to figure out the disposition of NF is FE-SEM imaging. This technique discloses the properties of NF, such as the shape of nanoparticles, sedimentation and nanoparticle sizes, etc.

As an example, the study [6] utilized FE-SEM imagery using a Nova Nanosem 450 instrument, which can operate under various pressures and achieve magnifications of up to 500,000x. The instrument's beam voltage can be adjusted between 200 V and 30 kV. Sample arrangement involved locating a NF sample onto a copper holder, drying it, and then coating the samples with a gold and palladium alloy to enhance electron transmissibility.

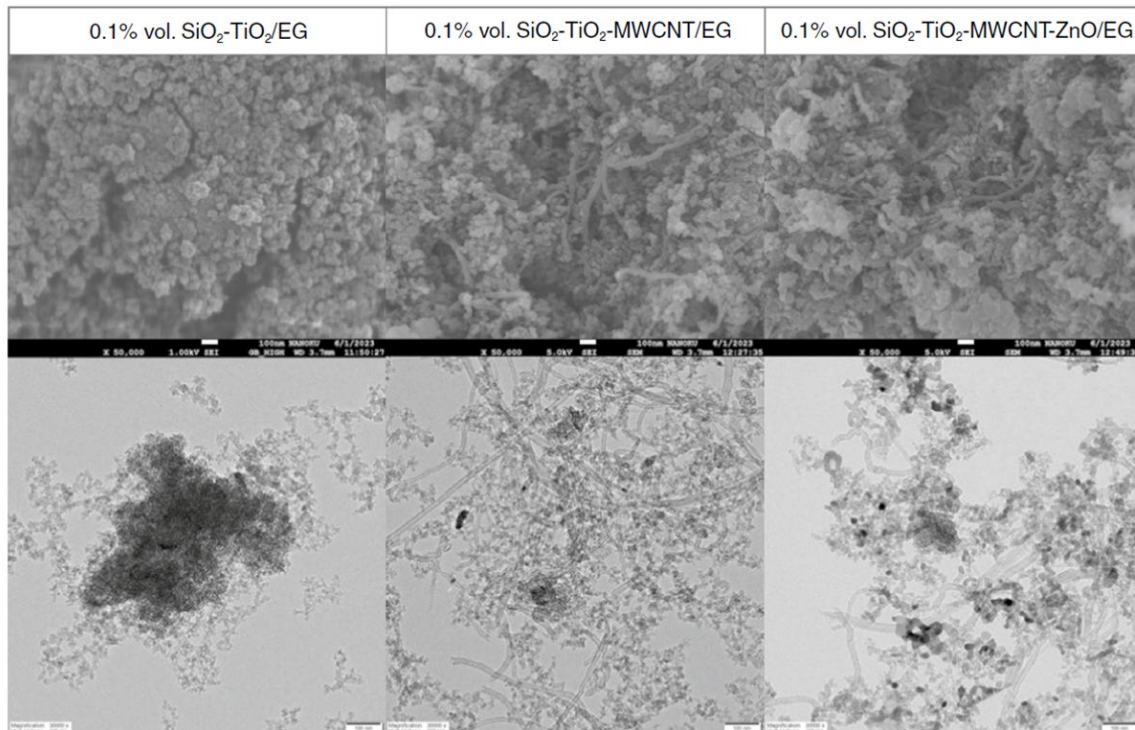


Fig. 9. FE-SEM (top, 50,000×) and FE-TEM (bottom, 30,000×) images of hybrid nanofluids [from Atmaca et al. [4] with permission from Elsevier]

As such, there are not any contamination views after drying in FE-SEM images of HNFs. A homogenous spread in two spherical structures is seen for the SiO₂-TiO₂ nanoparticles, as the SiO₂-TiO₂-MWCNT-MWCNT nanoparticles are of cylindrical tubes uniformly scattered between two spherical structures. As can also be observed from Figure 9, all three nanoparticles are of an evenly spread structure. The images have been demonstrated at 50,000× magnification.

3.1. Measuring Thermal Conductivity. Thermal conductivity is a crucial property for NFs, commonly measured using the hot wire method in Figure 10. There are several major components to this figure. The sample material has been involved in a 250 mm long; 25 mm diameter cylinder made of polypropylene. The hot wire cell is a Teflon-coated platinum wire of 190 mm and of diameter 76.20 μm. Furthermore, the thickness of the Teflon is 31.75 μm. The KD 2 Pro thermal conductivity analyzer system, shown in Figure 11, is widely used by researchers and used at ambient pressure. Temperatures are controlled by using a heating-cooling water bath within thermal conductivity measurements, dynamic viscosity measurements, and nanofluid sample preparation.

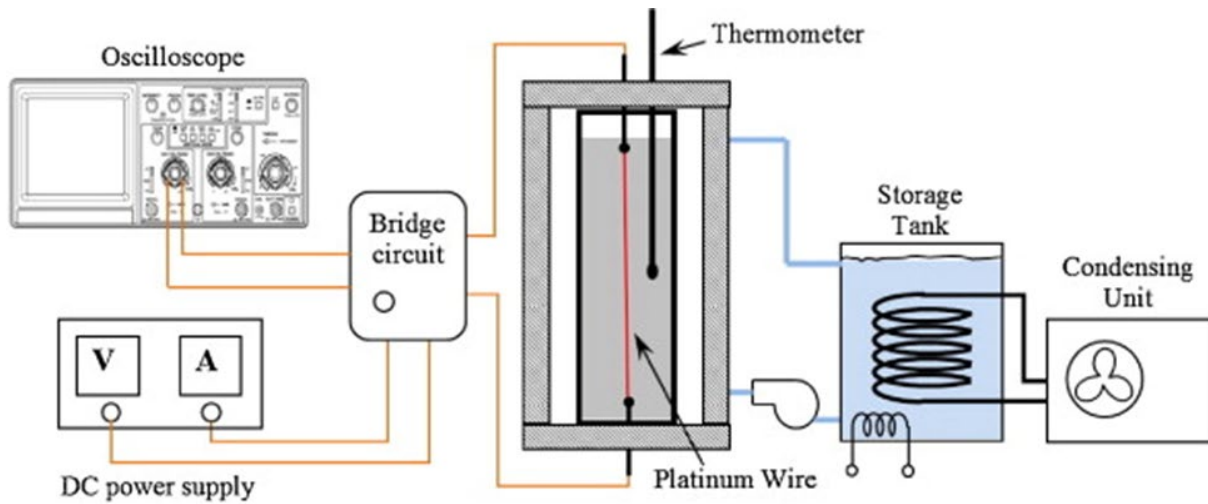


Fig. 10. The transient hot wire apparatus [from Yiamsawasd et al. [7] with permission from Elsevier]

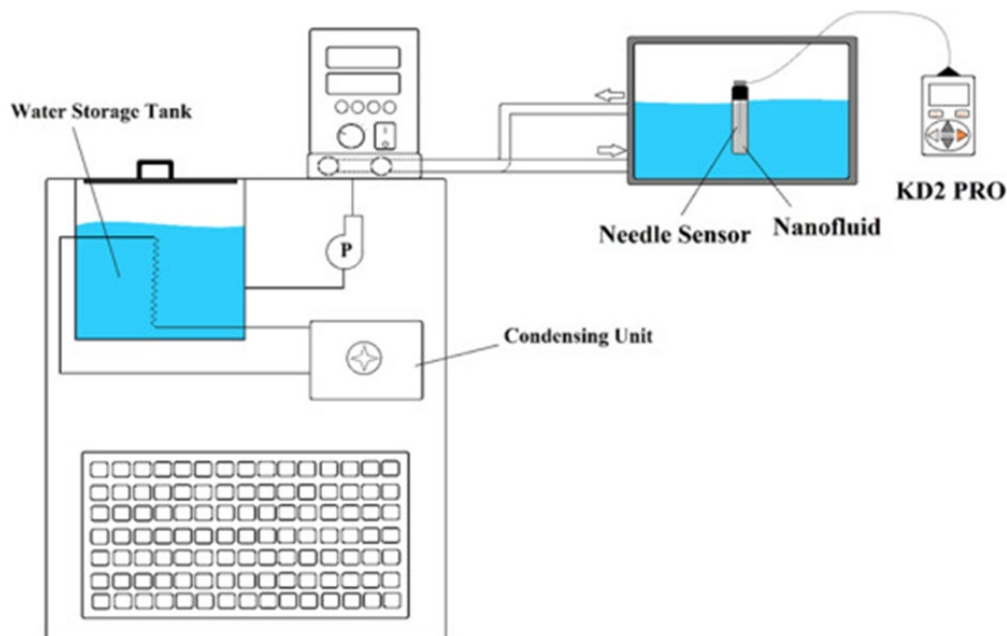


Fig. 11. An example of a typical experimental setup for thermal conductivity research [from Dalkilic et al. [8] with permission from Elsevier]

The experiment apparatus in Figure 11 consists of three discrete key components. Heating-cooling water baths, ultrasonic homogenizer, and thermal conductivity analyzer comprise that apparatus. The heating-cooling water bath can be operated between temperatures $-10\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ and has been used within $25\text{ }^{\circ}\text{C}$ - $60\text{ }^{\circ}\text{C}$ in the work in the literature. Ultrasonic homogenizer (Hielscher UP200Ht) can be utilized between capacities of 0 and 200 W, and from 0 to 26 kHz.

3.2 Measuring Thermal Conductivity. Prior to measurements, KD 2 Pro thermal conductivity analyzer should be calibrated by di-water, and the outcomes of the contrast with reference data [9] are illustrated in Figure 12 as an example. In this figure, a deviation of 2.2% has been noticed between experimental and reference thermal conductivity data [10]. Initially, the necessary amounts of samples (100 mL) are mixed by the homogenizer for one hour. Afterward, samples have been put into the water bath for thermal balance. Then, measurements are drawn and recurred three times by KD 2 Pro thermal conductivity analyzer. The average results have been determined as the results.

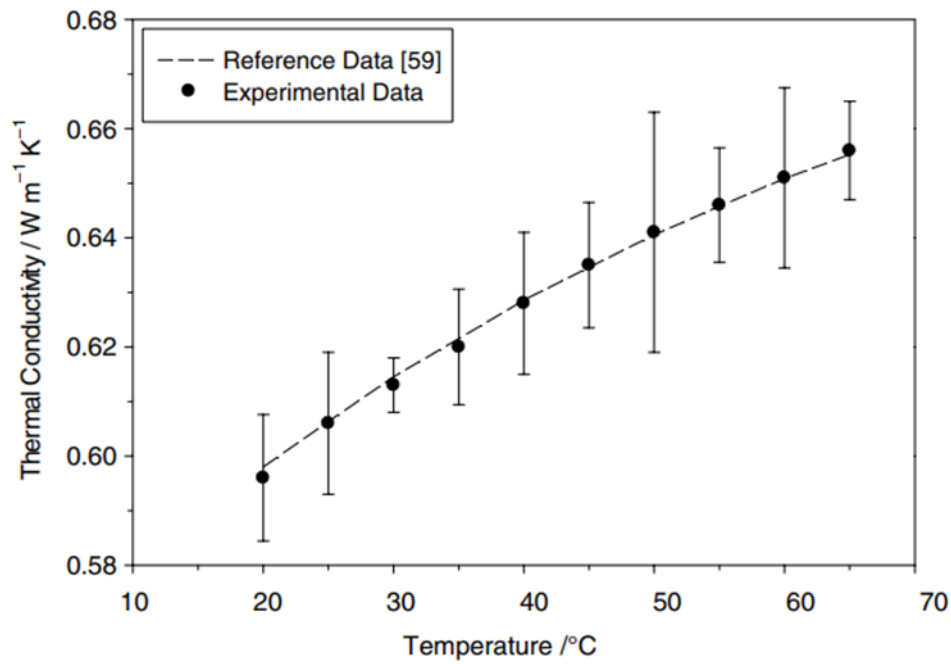
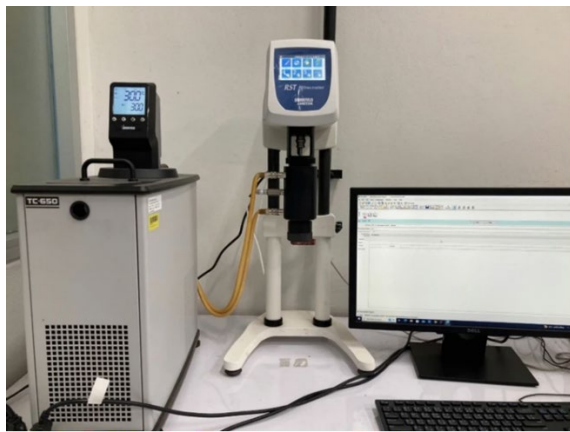
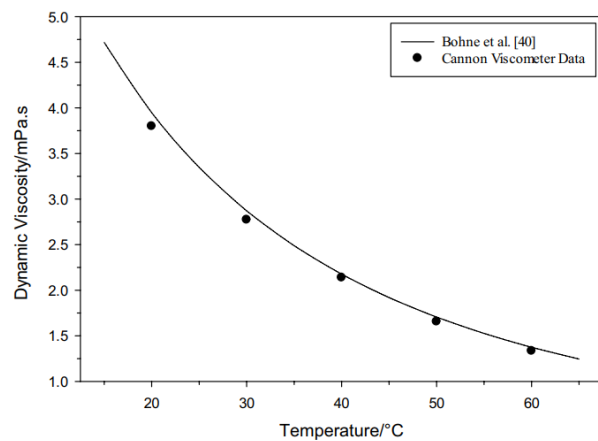


Fig. 12. Comparison of thermal conductivity findings with reference data [9] apparatus [from Yalcin et al. [10] with permission from Elsevier]

For example, a Cannon-Fenske opaque viscometer, as shown in Figure 13a, can be used for accurate measurements of viscosity in nanofluid samples, with an accuracy of $\pm 0.2\%$. Base fluid viscosity measurements are compared with reference data before using nanofluid samples, as shown in Fig. 13b.



a)



b)

Fig. 13. Experimental setup for viscosity measurement [from Dalkilic et al. [11] with permission from Elsevier] (a) and comparison of measured data with reference one [6] (b)

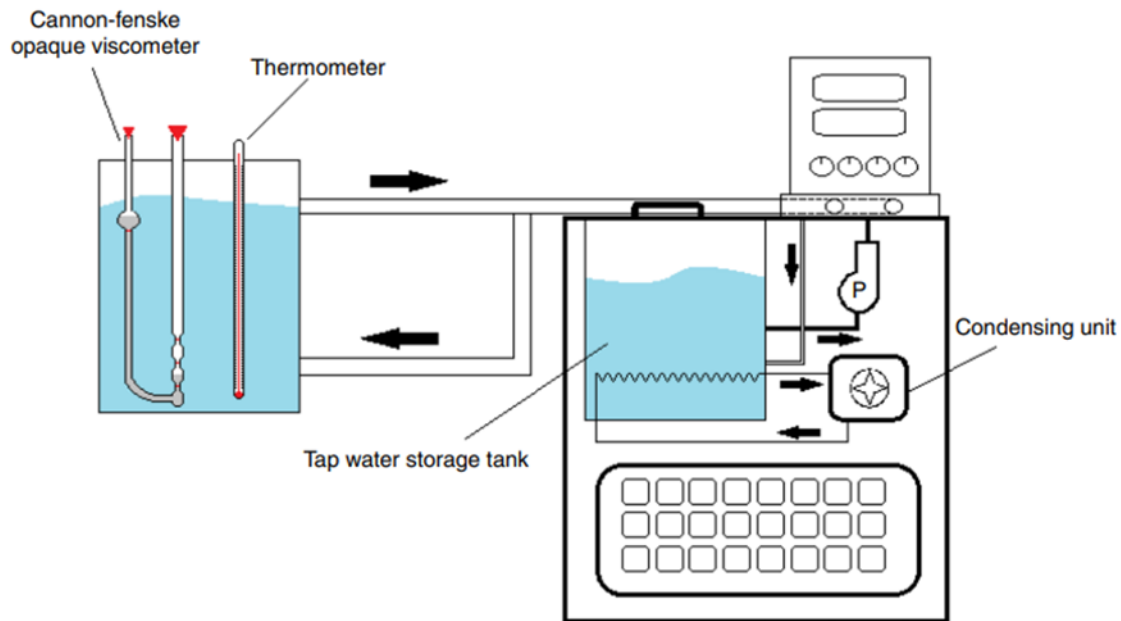


Fig. 14. Experimental setup for viscosity measurements [from Yalcin et al. [6] with permission from Elsevier]

Moreover, the depiction of the experimental apparatus is demonstrated in Figure 14. By means of a Hielscher UP200HT ultrasonic homogenizer adjusted to the highest capacity and frequency, by two hours the samples were homogenized. Eq. (2) is employed to calculate dynamic viscosity.

$$\mu_{nf} = c \times t \times \rho_{nf} \quad (2)$$

where c (cSt/s) is a coefficient that is described by the device producer, and each viscometer has a distinct coefficient. The variable, t , is time in seconds, which is employed to describe the movement of NF in the viscometer tube. ρ (kg/m^3) is the density of the prepared NF sample. Density can be revealed by Pak and Cho's [13] equation.

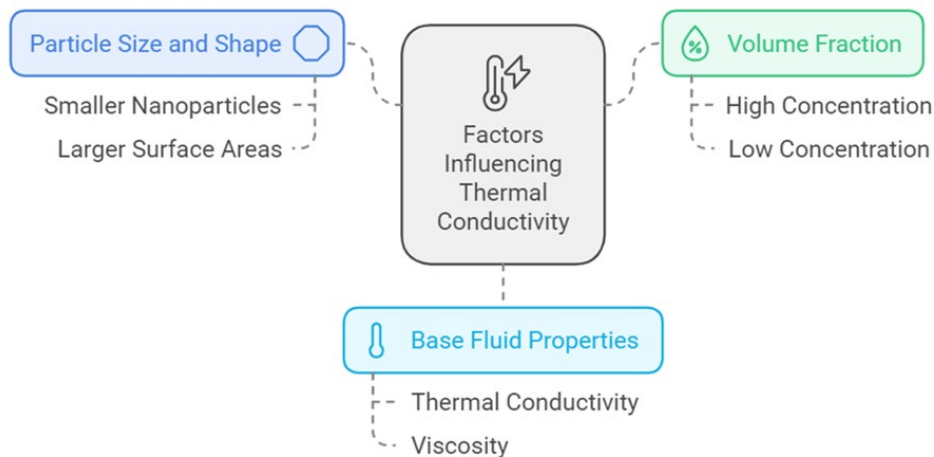


Fig. 15. The factors that influence thermal conductivity of HNFs

Fig. 15 outlines the ingredients impacting the thermal conductivity of HNFs and their influence on thermal transfer applications. It categorizes factors into blue for nanoparticle characteristics, green for volume fraction, and light blue for base fluid properties. The graphic emphasizes the importance of nanoparticle size and shape, with smaller nanoparticles and larger surface areas being critical. The volume percentage of nanoparticles in the base fluid is also crucial, with high and low concentrations suggesting optimal heat conductivity.

4. Studies related to thermal conductivity of hybrid nanofluids

4.1. Binary hybrid nanofluids' thermal conductivity

Although a significant number of studies have been conducted on HNFs thus far, there has still been a blank to be filled in this area. The thermal conductivity of developed NFs is of great significance with respect to heat transfer processes, since higher thermal conductivity results in better heat transfer rates. Mechanism in the interaction between nanoparticles and comprehending internal physics quite matter regarding thermal conductivity. Without conceding in thermal conductivity, in different working conditions the stability of HNFs should be examined. Additionally, alteration of thermal resistance according to parameters such as nanoparticle size, shape, concentration, nanopowder material, and base fluid employment is required as well. Accurate estimation of thermal conductivity through theoretical models can bring about effective design of heat exchangers in industry.

4.2. Ternary hybrid nanofluids' thermal conductivity

Heat transfer characteristics pertaining to HNFs have rendered them an accepted substitution for conventional heat transfer fluids thanks to their enhanced thermophysical properties. Pumping power, flow behavior, and performance of thermal systems are also affected by dynamic viscosity. The study uncovers the effect of base fluid sort, nanofluid concentration, temperature, shear rate, and viscosity over HNFs. In this regard, it is noted that high nanoparticle content advances thermal conductivity but raises viscosity, which may lead to high pressure losses and hence energy consumption rates. Experimental and modelling investigations have mainly been carried out to comprehend these dynamics spanning many nanomaterial combinations and preparation methods. Critical thermal efficiency and flow optimization of HNFs have recently been the core focus of many works. Influencing ingredients and insights suggested for better advancements are emphasized in this section.

Encouraging outcomes have been received from studies associated with ternary HNFs, whereas there have still been gaps to be filled. Owing to causing more complications compared to binary types, three different nanoparticle sorts are assessed to be more challenging in terms of estimating and regulating their configuration in the base fluid. Relations between nanoparticles, the sort of nanoparticles, and the base fluid comprise the factors determining the thermal performance. In this regard, figuring out the thermal resistance on heterogeneous interfaces is significant. The stability of HNFs is dependent on optimizing the size, arrangement, and proportions of nanoparticles. Because of HNFs' composition, size, and thermal characteristics, the selection of nanoparticles is quite challenging. More attention is needed in the future to improve HNF stability.

Figure 16 presents experimental observations of dynamic viscosity from the work of Yalcin et al. [10]. The dynamic viscosity outcomes had an uncertainty interval of $\pm 3.6\%$. In line with the dynamic viscosity results, the lowest dynamic viscosity variation was found to be 7.29% , corresponding to 0.5% ZnO 0.66-SiO_2 0.33 at the temperature of $50\text{ }^\circ\text{C}$, as the maximum dynamic viscosity alteration was observed to be 13.6% , which was referring to 1% ZnO 0.33-SiO_2 0.66 at $50\text{ }^\circ\text{C}$.

5. Hybrid nanofluids hybrid nanofluids' dynamic viscosity studies

5.1. Studies related to dynamic viscosity of binary hybrid nanofluids.

As depicted in Figure 17, by scrutinizing features such as base fluid preference, temperature, and nanoparticle concentration and their impacts on their characteristics, dynamic viscosity of HNFs is explored. The figure emphasizes the compromise between thermal performance and viscosity, such that growing nanoparticle concentration by and large is enhancing thermal conductivity while growing viscosity which causes higher pressure drops and thus work to transfer the fluid and operating costs.

The dynamic viscosity of HNFs remains underexplored, necessitating a comprehensive rheological investigation across various shear rates, temperatures, and pressures. Techniques like TEM, SEM, DLS, and SANS can be used to examine the binary HNF microstructure and nanoparticle distribution, which directly affect viscosity. However, current theories may not be applicable to binary HNFs, necessitating the development of innovative models to accurately measure these systems' interrelations and microstructure. Such knowledge is crucial for determining pressure loss in flow systems and assessing pumping power requirements.

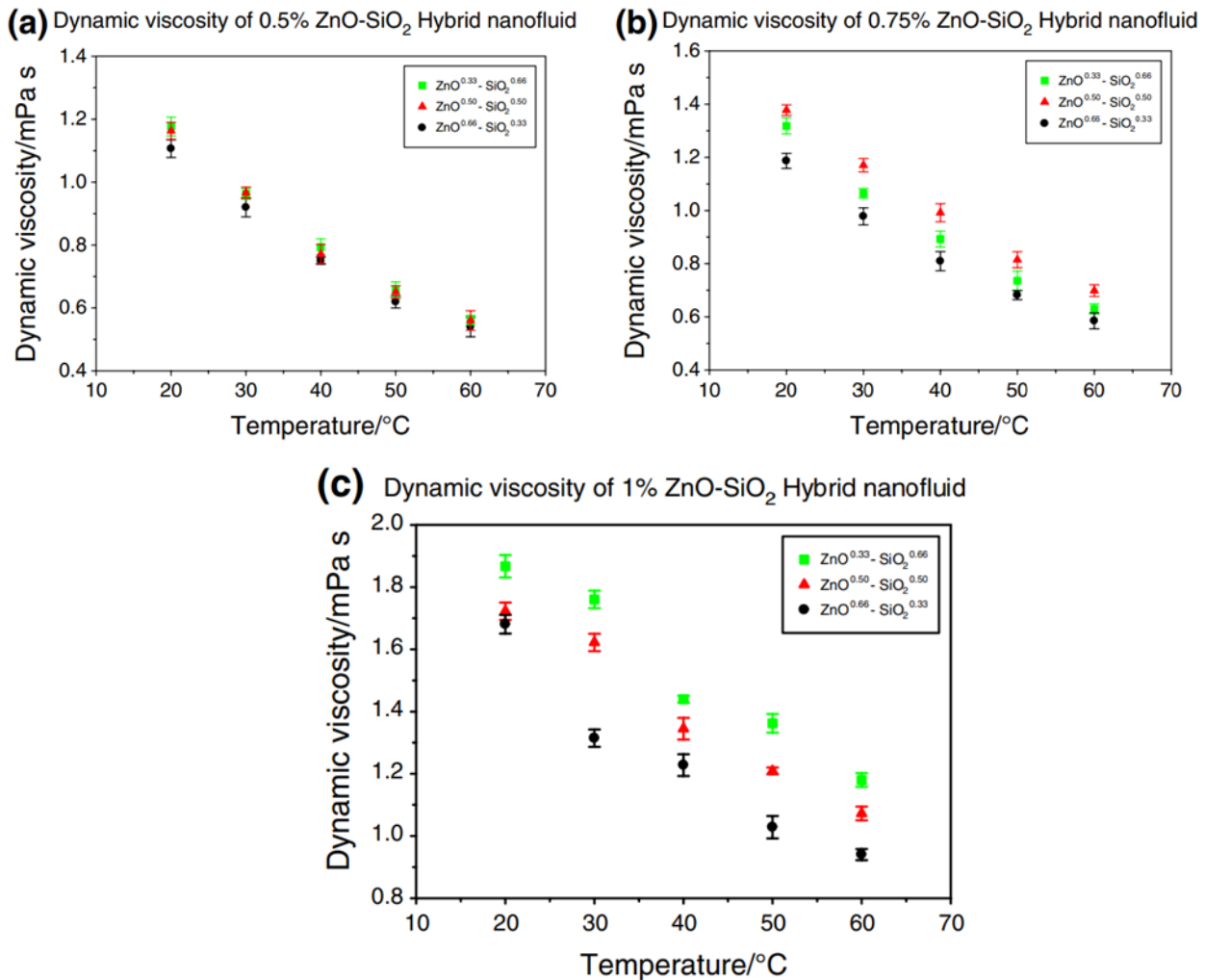


Fig. 16. Dynamic viscosity alteration of ZnO-SiO₂ [from Yalcin et al. [10] with permission from Elsevier]

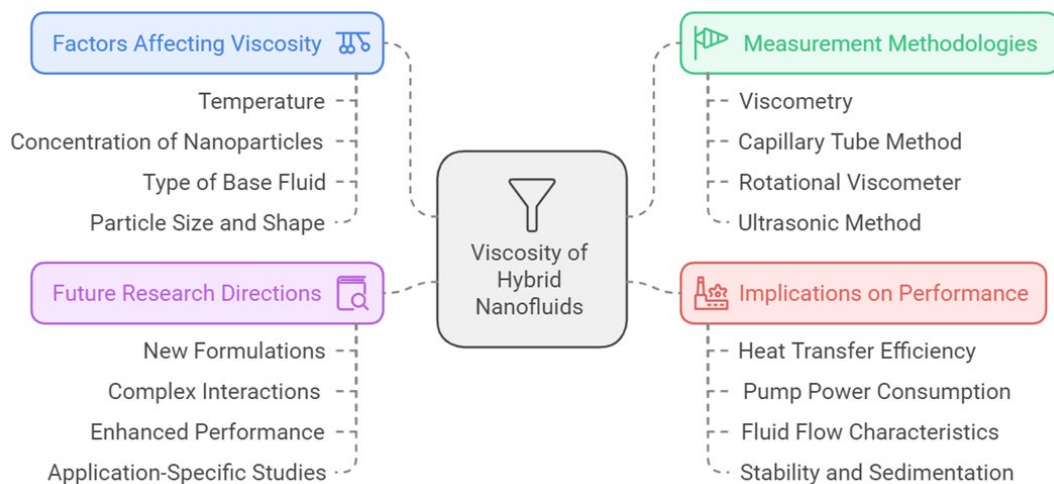


Fig. 17. The affecting factors, future research directions, measurement methods, and performance implications of viscosity of HNFs

5.2. Dynamic viscosity studies of ternary hybrid nanofluids. This section indicates the dynamic viscosity of ternary HNFs and the impact of nanoparticle combinations, temperature, and concentration

on these fluids. Unlike simple Newtonian fluids, ternary nanofluids often have non-Newtonian properties, complicating viscosity behavior. Multi-objective optimization techniques are required owing to the interaction between the base fluid and nanoparticle surfaces generating complex lubricating layers. The distribution and form of nanoparticles considerably affect the viscosity, which also influences the reachable highest concentration prior to getting maximum limits of viscosity. A method integrating engineering, material science, and computer modelling while considering viscosity, thermal conductivity, and pressure drop is necessary for optimized ternary NFs.

For example, Figure 18 shows that all NF concentrations, except for the one with SiO₂ nanoparticles, precipitated during stability tests. HNFs of 0.1% concentration were utilized in following tests. An initial binary HNF was created using SiO₂ and TiO₂ nanoparticles. After 28 days, a viscosity measurement was carried out on the fractions, employing a setting ratio of SiO₂–TiO₂ (1:1). Figure 18a contrasts the binary nanofluid with the base fluid and single nanofluids, encompassing SiO₂ and TiO₂. In comparison to ethylene glycol and single nanofluids, the binary hybrid nanofluid resulted in a lower dynamic viscosity. In addition to SiO₂ and TiO₂ nanoparticles, to generate ternary nanofluids, MWCNT nanoparticles were also employed. Since MWCNT nanoparticles are of a lower viscosity than ZnO, for the ternary nanofluid generation process, they were preferred.

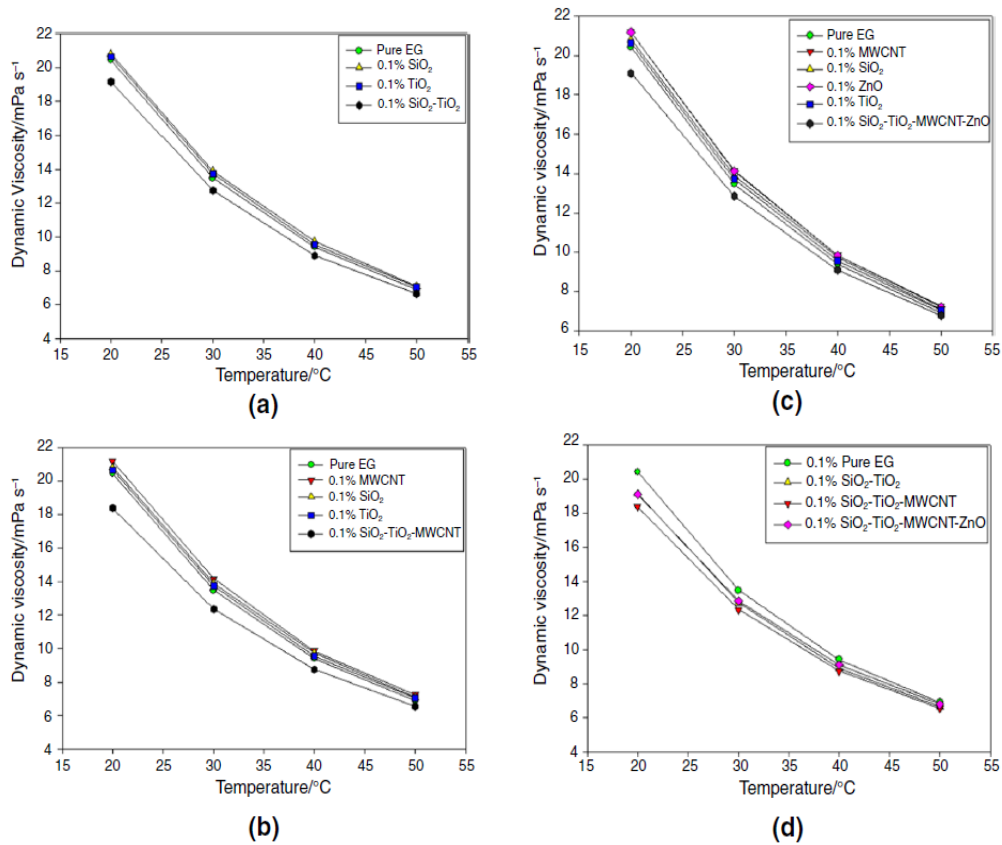


Fig. 18. Comparison of dynamic viscosities of a binary, b ternary, and c quaternary nanofluids with their components, and comparison of dynamic viscosities of hybrid nanofluids [from Atmaca et al. [4] with permission from Elsevier]

6. Multiple thermophysical characteristics studies of hybrid nanofluids. This part explores the thermophysical properties of HNFs, including viscosity, thermal conductivity, density, heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, and heat transfer efficiency. It also tracks stability-related metrics like zeta potential and thermal efficiency to ensure long-term suitability in various thermal settings. The study examines the relationship between these thermophysical characteristics and their impact on operating conditions, temperature, base fluid type, nanoparticle concentration, and shape. By comparing the efficiency of HNFs to binary and mono

equivalents, the influence of different nanoparticle groupings and concentrations has been reported in the literature. HNF was created by Kishore et al. [14] using CTAB and distilled water to produce copper-graphene hybrid nanoparticles. Although no stabilizer has been employed, nanofluids have kept their stabilities, and their thermophysical properties have been observed. Contrary to the distilled water, an HNF of 0.02% has raised density, viscosity, and thermal conductivity approximately by 9.95%, 13.5%, and 12.5%, respectively.

7.Conclusion. This paper unveils the strong potential of HNFs particularly in thermal processes, by highlighting their exceptional traits and applications. The literature has been classified by binary and ternary thermophysical properties also referring to their heat transfer rate, heat transfer coefficient, friction factor, thermal performance factor, Nusselt number, heat transfer efficiency, zeta potential, stability, thermal efficiency, isobaric heat capacity, and specific heat capacity. HNFs are recognized for their better thermophysical properties and increased stability, making them a suitable candidate for a solution for single NFs. The findings suggest that strategically combining multiple nanoparticles within a base fluid can improve viscosity, thermal conductivity, and other performance aspects. Resurrection studies indicate that specific HNF compositions can increase the efficiency of thermal systems, particularly in heat exchangers, thermal solar collectors, cooling photovoltaic panels, and electronics cooling systems. Even though there is extensive literature published on the thermal properties of HNFs, there are still gaps that need to be addressed, such as

- a. A favorable synthesis being generated, which is both profitable and reasonable for examining the thermophysical properties of HNFs.
- b. Especially to render them appropriate for electronic cooling applications, comprehending the heat transfer and flow mechanism of HNFs in microchannels.
- c. Single phase flow visualization study of HNFs at different flow conditions would be beneficial for the present industries that focus on thermal management.
- d. Development of generalized or specific theoretical models and development of correlations to calculate the thermophysical properties of HNFs.
- e. Usage of suitable surfactants, by maintaining a good balance between stability and effective thermal conductivity of HNFs.
- f. Possibilities of employing these HNFs in heat pipes and thermosyphons, which work particularly in two-phase and optimize their usage with a reasonable trade-off between nanoparticle settlement and heat transfer.

Lastly, this paper offers a thorough overview of current research on the thermo-physical properties of NFs and how they enhance heat transport in a variety of applications. Although HNFs have a bright future, industrial deployment is still a way off due to stability issues, which are the main problem facing NFs. Their uses are anticipated to grow as research into these complex fluids deepens our understanding of them, resulting in more sustainable and effective thermal management solutions across a range of sectors.

Acknowledgement. The first author, Ahmet Selim Dalkılıç would like to acknowledge the support from by European Union's Research and Innovation Program Horizon Europe under the Marie Skłodowska-Curie grant agreement (No 101130406) and UKRI Engineering and Physical Sciences Research Council (EP/Y036662/1). He also would like to acknowledge the support from the Scientific Research Department, Azerbaijan University of Architecture and Construction in Azerbaijan, with the permission from the Ministry of Science and Education of the Republic of Azerbaijan under the protocol on international cooperation between YTU and AzUAC dated 16.04.2025.

Declaration of generative ai and ai-assisted technologies in the writing process. During the preparation of this work, the authors used QuillBot to improve the writing and English of some sections. After using this tool/service, the authors reviewed and edited the content as needed, and they take full responsibility for the content of the publication.

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Received: 07/09/2025 Accepted: 16/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-39-45>

THE FUTURE OF SMART AND SUSTAINABLE CITIES: A GLOBAL PERSPECTIVE ON INFRASTRUCTURE INNOVATION

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Abstract. As cities face increasing demands for climate resilience, rapid urbanization, and digital change, infrastructure innovation becomes a crucial element for sustainable urban futures. This study examines the changing frameworks of smart and sustainable cities from a global perspective, highlighting the essential contributions of planners, politicians, and urban innovators in developing adaptive, inclusive, and technologically connected infrastructure systems. The lecture, anchored in international policy frameworks like the UN Sustainable Development Goals, the New Urban Agenda, and ISO Smart Community Standards, elucidates how multi-level governance, citizen engagement, and public-private partnerships are transforming urban infrastructure. Utilizing innovative urban models from Singapore, Songdo, and Masdar City, it demonstrates scalable approaches in retrofitting, digital twins, nature-based solutions and resilient mobility systems. The lecture emphasizes the relationship between physical infrastructure and digital ecosystems, focusing on data-driven governance, ethical technology integration and equitable infrastructure. It concludes by redefining infrastructure as not only physical assets but also as dynamic, socially integrated systems that promote long-term urban sustainability, adaptability and equity in an increasingly interconnected world.

Keywords: sustainable urban futures, smart cities, climate resilience, rapid urbanization, digital ecosystems

1. Introduction: reframing urban futures via infrastructure innovation. In the twenty-first century, urban infrastructure is not exclusively characterized by the provision of physical amenities such as roads, pipelines and energy grids. It is widely acknowledged as a dynamic and adaptive system that supports cities' abilities to address climate change, swift digitalization, and changing social expectations (Graham & Marvin, 2001; Angelidou, 2015). This reconfiguration signifies a pivotal transition from rigid, utility-centric frameworks to multifunctional, interconnected systems that amalgamate technological, ecological and social aspects. Contemporary infrastructure prioritizes the development of adaptable, resilient networks over the engineering of static assets, facilitating urban transformation (Neuman, 2006; Coutard & Rutherford, 2015).

Urban planners play a crucial role in this change. Planners have evolved from being just technical implementers of projects to being strategic system thinkers and institutional entrepreneurs. They facilitate innovation processes that span governance domains, digital technologies and sustainability transitions. Davoudi (2012) contends that modern planning necessitates reflexivity, interpretive acumen, and foresight to restructure comprehensive urban systems, particularly during periods of uncertainty and upheaval. Planners are thus pivotal in transforming infrastructure into a catalyst for systemic change rather than a mere backdrop to urban existence (Bulkeley et al., 2016).

The advent of Smart Sustainable Cities (SSCs) illustrates this paradigm shift. Smart Sustainable Cities (SSCs) are characterized by their capacity to utilize modern technology and innovative planning frameworks to enhance sustainability, resilience and quality of life (Kommunos, 2013; Bibri & Krogstie, 2017). Their principal attributes encompass effective resource management, diminished

environmental impacts, inclusive governance frameworks, and resilient infrastructures adept at adapting to shocks and stressors. Digital technologies, including big data, IoT (Internet of Things), and AI-driven platforms, are pivotal in facilitating real-time monitoring and decision-making (Caragliu, Del Bo, & Nijkamp, 2011; Bibri, 2018). Nonetheless, SSCs are not solely technological entities. Their efficacy hinges on institutional and social innovation, necessitating novel forms of collaboration, citizen involvement and participatory governance (Nam & Pardo, 2011; Hajer & Dassen, 2014).

This paper positions infrastructure innovation as central to urban futures by redefining it as a catalyst for comprehensive systemic transformation, rather than merely a specialized technical service. The connections among intelligence, sustainability, and resilience provide a framework for analyzing how cities might strategically respond to global challenges while also meeting local demands for equity, inclusivity and livability.

2. Converging crises and the necessity for infrastructure reenvisioning. The necessity to reevaluate infrastructure stems from the intersection of multiple global challenges. Accelerated urbanization, coupled with increasing demands for climate adaption and decarbonization, is straining urban systems beyond their current capabilities. By 2050, the global urban population is projected to attain 68%, resulting in unparalleled demand for housing, transportation, energy, and water (United Nations, 2019). These pressures jeopardize the stability of existing systems that are already strained in numerous locations.

A significant difficulty is that a considerable portion of the world's infrastructure is deteriorating, outdated or not maintained. The World Bank (2019) predicts that bridging the infrastructure investment deficit necessitates trillions of dollars per year. In the absence of reinvestment, cities jeopardize their operations by relying on antiquated systems that are inadequate for addressing the escalating challenges posed by climate change, digital connection, and urban expansion (Rozenberg & Fay, 2019). Problems of energy inefficiency, water shortage and unsustainable transportation are especially severe. These issues cannot be addressed independently, as they are intricately linked within social, ecological and technological systems (Markolf et al., 2018). Resolving these issues necessitates systemic innovation, comprehensive planning and interdisciplinary governance strategies.

Climate change introduces an additional level of urgency. Infrastructure systems both contribute to greenhouse gas emissions and are significantly susceptible to climate impacts, including heatwaves, floods and sea-level rise (IPCC, 2022). Adaptation necessitates the reconfiguration of infrastructure to enhance climate resilience, concurrently facilitating mitigation via decarbonization and energy transitions. The dual necessity of adaptation and mitigation positions infrastructure as crucial to planetary survival.

In addition to environmental and technical challenges, the digital transformation in urban government has introduced new inquiries of equity and justice. Although digital infrastructures and smart city efforts offer potential efficiency improvements, they may intensify disparities if access is not equitably allocated (Van Dijk, 2020; Townsend, 2013). Concerns regarding digital inequality and spatial justice are now inextricably linked to discussions about infrastructure. Fainstein (2010) and Soja (2010) assert that infrastructure is politically charged; it determines the beneficiaries and the individuals who endure the hazards of urban transformation.

Collectively, these constraints underscore the necessity for infrastructure to be not merely reconstructed but re-envisioned. Future infrastructures must function as instruments of resilience, sustainability, and justice, allowing cities to stay adaptable, equitable and prepared for future difficulties.

3. Global policy frameworks and guiding principles. The evolution of urban infrastructure is not happening in isolation. It is increasingly directed by global policy frameworks and guiding concepts that serve as navigational aids for national and local governments. The United Nations Sustainable Development Goals (SDGs), especially SDG 11 (Sustainable Cities and Communities), have emerged as a fundamental worldwide benchmark for urban development (United Nations, 2015). The Sustainable Development Goals delineate explicit aims and indicators, connecting local urban policies to a global agenda of sustainability, resilience and inclusivity.

The New Urban Agenda (Habitat III, 2016) solidifies this commitment by offering a

transformational framework for sustainable urbanization. It underscores the significance of integrated, participatory, and inclusive planning methodologies as crucial for tackling urban challenges of the twenty-first century (UN-Habitat, 2017). Collectively, these frameworks offer normative guidance, linking urban policy with global sustainability objectives.

In addition to aspirational objectives, worldwide standardized frameworks have developed to offer practical tools. Standards like ISO 37120 (Indicators for City Services and Quality of Life), ISO 37122 (Indicators for Smart Cities), and ISO 37123 (Indicators for Resilient Cities) facilitate cities in benchmarking performance, assessing progress and sharing information globally (ISO, 2019). For planners, such instruments establish a foundation for evidence-based planning; yet, their efficacy is contingent upon local capacity, institutional backing and political resolve.

The primary problem is translation: converting global ideas into actionable initiatives at the local level. This necessitates a multi-tiered governance framework, wherein global objectives are contextualized, national policies provide coherence, and local activities reflect community realities (Bulkeley & Betsill, 2013). The primary objectives of this translation encompass promoting sustainable development trajectories, expediting digital transformation, integrating energy efficiency and cultivating citizen-focused innovation (Hajer & Dassen, 2014).

Numerous initiatives illustrate the global context influencing infrastructure innovation:

- Sustainable Development Goals (SDGs): SDG 11 offers a comprehensive framework, advocating for cities to be inclusive, secure, resilient and sustainable (United Nations, 2015).
- The New Urban Agenda advocates for integrated and participatory planning as a revolutionary approach to achieving sustainable urbanization (UN-Habitat, 2017).
- The Global Covenant of Mayors on Climate & Energy exemplifies the voluntary, grassroots dedication of local governments to address climate change (GCoM, 2021).
- ISO Standards offer internationally acknowledged frameworks for evaluating sustainability, intelligence, and resilience (ISO, 2019).

These frameworks collectively underscore the interconnectedness of strategic foresight, benchmarking, and participatory governance in the quest for sustainable infrastructure innovation.

The achievement of global objectives relies on financial and institutional capabilities. Financing infrastructure innovation continues to be one of the most significant concerns of our era.

- Multilateral Development Banks (MDBs), including the World Bank, Asian Development Bank, and African Development Bank, are essential for financing extensive infrastructure projects. They offer concessional loans, grants, and technical assistance, frequently associating projects with global frameworks such as the Sustainable Development Goals and climate adaption initiatives (World Bank, 2019). The World Bank's Urban Resilience Program has facilitated flood mitigation in Jakarta and Accra by integrating infrastructure financing with technical skills.
- The Green Climate Fund (GCF) functions as a specialized financial vehicle under the UNFCCC, offering support for climate-resilient and low-emission urban infrastructure. The focus on fairness guarantees that disadvantaged cities and regions obtain access to resources (GCF, 2021).
- Blended finance arrangements are increasingly recognized as creative strategies to attract private sector investment. By integrating public or charitable resources with private investment, they mitigate risk and facilitate new funding streams for high-cost, long-term infrastructure initiatives. Platforms like the Global Infrastructure Facility illustrate how blended finance may stimulate investment in resilient and intelligent urban infrastructure (CPI, 2022).
- Public-business Partnerships (PPPs) enhance financing prospects by facilitating co-governance between governmental entities and business stakeholders. When well designed, public-private partnerships enhance efficiency, innovation and scalability in urban service provision. Illustrations encompass intelligent lighting systems, cohesive mobility platforms, and advanced water networks (OECD, 2015). Nonetheless, public-private partnerships necessitate open governance structures, robust social protections and the institutional capability of local authorities to guarantee equitable results.

Funding methods encompass not just financial resources but also institutional and political innovations that influence the governance of infrastructure transformation.

4. Infrastructure innovation in practice: global city examples. Global examples elucidate the practical implementation of frameworks, finance and innovation (Table 1).

- Singapore's Smart Nation strategy exhibits the integration of digital infrastructure, participatory governance and sustainable building efforts, illustrating how long-term planning may harmonize intelligence with sustainability (Smart Nation, 2023).
- Songdo (South Korea): Engineered as a high-tech, master-planned city, Songdo exemplifies the potential and obstacles of technology-centric strategies for sustainability (UN-Habitat, 2019).
- Masdar City (UAE): A low-carbon center in a desert environment, Masdar incorporates renewable energy, sustainable design and global cooperation in innovation (WEF, 2022).
- Amsterdam (Netherlands): Champions circular economy ideas with its Amsterdam Smart City initiative, highlighting collaboration, economic sustainability and knowledge transfer (ASC, 2021).
- Tokyo (Japan): Exemplifies how established megacities may adapt existing infrastructures via energy efficiency enhancements, sustainable building standards and digital management systems (Tokyo Metropolitan Government, 2025).

These instances exemplify the variety of approaches cities may pursue, ranging from technology-oriented master planning to circular retrofitting and governance-led reforms.

Table 1. Comparative Evaluation of Global City Cases in Infrastructure Innovation

City	Core Strategy	Sustainability Focus	Smart/Tech Approach	Governance & Participation	Financing & Partnerships	Key Challenges / Critiques
Singapore	Smart Nation with integrated planning	Green buildings, energy efficiency, water recycling	IoT, AI, real-time data systems	Centralized but participatory (URA, GovTech, citizen apps)	State-driven with some PPPs	Centralization may limit bottom-up innovation
Songdo (South Korea)	Master-planned smart city from scratch	District heating, waste systems	ICT backbone; sensors embedded throughout	Top-down governance, limited community input	International consortia (Gale Intl., Korean gov.)	Criticized for lack of livability, weak social fabric
Masdar City (UAE)	Low-carbon eco-city in arid context	Renewable energy, green architecture, carbon neutrality	Smart grids, clean-tech clusters, energy monitoring	PPPs with global research institutions (e.g., IRENA)	State-backed + foreign investment	Low occupancy, economic viability challenges
Amsterdam (Netherlands)	Circular economy + collaborative smart city	Energy transition, material reuse, circular urbanism	Smart mobility pilots, integrated energy systems	Highly participatory, multi-actor collaboration	Municipal funding, EU grants, PPPs	Scaling pilots into systemic transformation
Tokyo (Japan)	Retrofitting and upgrading existing megacity	Green building standards, carbon mitigation via retrofits	Digital twins, smart energy management	City government-led with gradual citizen engagement	National subsidies, municipal + private sector	High retrofit costs, institutional inertia

5. Concluding remarks: retrofitting and circular infrastructure. Retrofitting constitutes a vital strategy for carbon mitigation and sustainability. Studies indicate that enhancing current buildings and infrastructure frequently yields superior environmental advantages compared to new development (Grubler et al., 2018). Adaptive reuse, energy retrofitting and circular urbanism strategies enhance durability, minimize material waste, and prolong asset lifespans. Amsterdam and Tokyo illustrate the integration of circular principles in urban regeneration, highlighting that sustainability involves reimagining existing assets as much as developing new ones (Ellen MacArthur Foundation, 2019).

The implementation of GIS, IoT, AI analytics, and digital twins is revolutionizing infrastructure management. These instruments enable municipalities to simulate situations, oversee systems in real time and incorporate data into decision-making (Batty, 2018). The emergence of digital infrastructures presents ethical and political dilemmas. Who possesses the data? What is the governing structure? Which individuals' perspectives are incorporated in algorithmic decision-making? Kitchin, 2014. Resolving these inquiries necessitates strong frameworks for ethical data governance, digital inclusivity and open-data transparency.

Infrastructure planning encompasses both technical and socio-political dimensions. Co-creation and participatory planning guarantee that infrastructure projects align with community priorities and prevent the aggravation of inequality. Participatory budgeting, citizen panels and internet participation platforms are becoming increasingly prevalent instruments (Fainstein, 2010). Furthermore, digital equality has emerged as a fundamental aspect of spatial justice. In the absence of equitable access to digital infrastructures, the potential of smart sustainable cities may exacerbate existing disparities (Soja, 2010).

Contemporary infrastructure transcends mere hardware; it serves as the fundamental framework for egalitarian, resilient and intelligent urban futures. Addressing the confluence of crises necessitates reconceptualizing infrastructure as an interconnected system, harmonized with global policy frameworks, funded through novel channels, and executed by participatory and inclusive governance. Planners are required to function as strategic systems thinkers that connect many sizes, disciplines and communities. Infrastructure innovation is essential for achieving planetary sustainability and urban justice, representing a significant challenge and opportunity of our century.

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Received: 07/09/2025 Accepted: 16/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-46-52>

A POWERFUL METHOD FOR STRESS ANALYSIS: THE PHOTOELASTICITY METHOD – SOME EXAMPLES FROM THE ITU EXPERIMENTAL MECHANICS LABORATORY

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Abstract. Stress analysis is a crucial step for a design or strength analysis. The methods of experimental analysis are indispensable for validation when the approximations in the analytical and numerical methods are taken into account. As one of the first experimental methods, photoelasticity offers a very useful way to analyze different models of transparent material. Not only two-dimensional stress analyses are performed with this method, but also a full three-dimensional analysis can be performed with the strain-freezing method based on the viscoelastic property of the material used. In the Experimental Mechanics Laboratory at Istanbul Technical University (ITU), various models from different research areas are produced and analyzed, from civil engineering to biomechanics or mechanical engineering to dental technology. This presentation summarizes some of the interesting experiments carried out in this laboratory.

Keywords: stress analysis, experimental analysis, validation of numerical methods, approximations, experimental mechanics

1.Introduction. An object that is exposed to external forces is subjected to certain deformations, which can be measured with special tools. During this deformation, the material of the object exhibits the result of the deformation, the so-called stress. Although it is a physical quantity, stress is defined in mechanics as an imaginary phenomenon with the force per unit area. It is not possible to visualize or to measure stress or its components. In terms of the continuum assumption, a material point is assumed to be under a state of stress, which is assumed to be a continuous variable over the volume of the object [1-3]. Engineers or designers need a comparative tool to evaluate the strength of their design and the stress with the quantity of strain, simply the unit deformation, is used as data for this evaluation. The stress state is predictable when the geometry and loading are not complex. However, in complex cases, as in most cases in nature, this state must be determined in order to explain the behavior of the object or design.

The theory of elasticity provides analytical methods for determining the stress field [1-4]. The difficulties in applying the solutions have been overcome by numerical methods. In this way, predictions can be made for many different complex problems. However, the predictions suffer from the degree of approximation, and one cannot say anything about the degree of approximation if one does not know the absolute solution. In fact, who can say that there is only one absolute solution to a case in nature, because no one guarantees that everything in the problem under consideration exists in the same way at all times. Nevertheless, the experimental methods with the simplified conditions provide the most reliable results for a given problem. Therefore, a validation of the analytical and numerical methods can be made on the basis of the experimental results [6, 7].

Validation brings accuracy to the proposed solution, and it can be done with a reliable method of analysis. In analytical modeling, there are some approximations and idealizations to construct the

equations. Moreover, the exact solutions of the analytical equations can only be obtained for very limited simple problems. Numerical solutions help us to solve complex problems, but there are many problems with this solution, such as rounding error, convergence, etc. Experimentation is an important way to validate the results of numerical or analytical analysis of a structure. Validation can be performed effectively if the experimental method and conditions for the experimental setup are properly defined, and the measurement instruments do not disturb the stress field of the model.

Photoelasticity is an experimental method based on the birefringence of light by an optically sensitive material under external loads. This method establishes a relationship between the optical anisotropy of the material and the stress distribution. Optically anisotropic materials refract light in two directions perpendicular to each other at different velocities when they are loaded. The difference in velocity varies from point to point depending on the stress value. The dark-field arrangement with two polaroid filters and two quarter-wave plates in a circular polariscope (Fig. 1) enables the fringe patterns of isochromatics with integer orders on a transparent model such as Araldite, an epoxy-based resin, as a result of the loading conditions. This is because the order is determined by the phase difference between two light components generated by the birefringence property of the material. The material is called an optically anisotropic material, which means that it refracts the light in two directions perpendicular to each other when it is loaded. The retardation is the result of the difference in the velocities of these perpendicular light components. One can view color patterns with different darknesses. In the dark-field arrangement, these color patterns, isochromatics, show the points where the difference of the in-plane principal stress is the same. In other words, along an isochromatic pattern, the difference of the in-plane principal stresses, $\sigma_1 - \sigma_2$, is a constant and the result of the order of the pattern. The relation is expressed as follows:

$$\sigma_1 - \sigma_2 = f_{\sigma} \frac{N}{h} \quad (1)$$

where f_{σ} , N and h are material fringe value, the order of the fringe pattern and the model thickness parallel to the light direction [5-7].

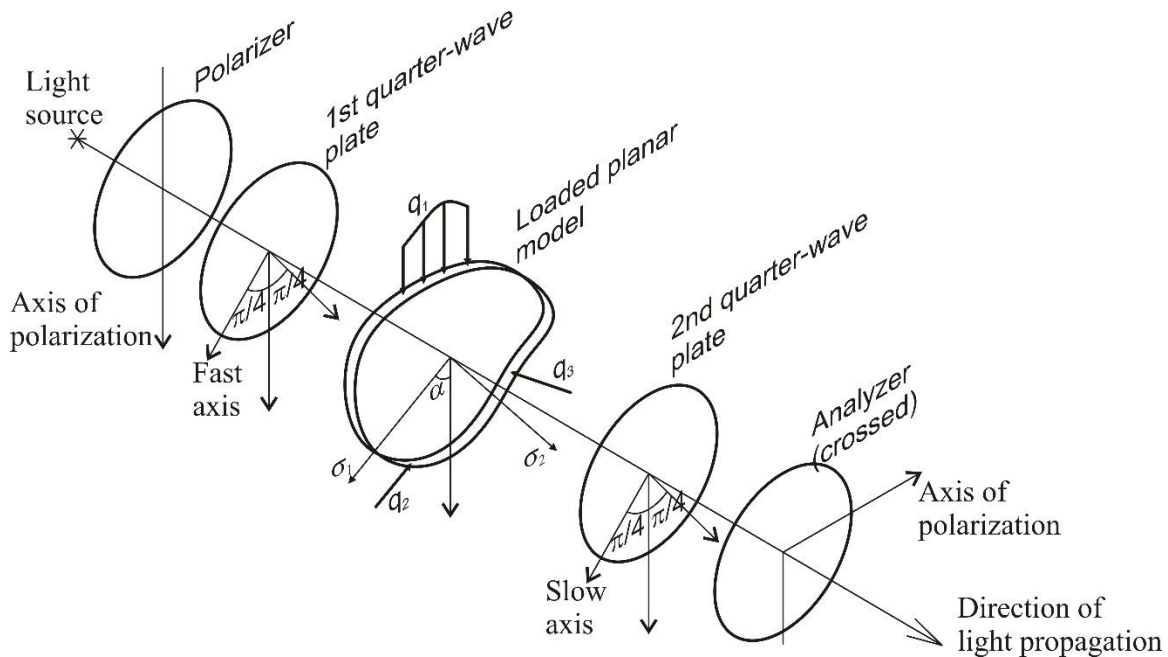


Fig. 1. The dark-field arrangement with two polaroid filters and two quarter-wave plates in a circular polariscope

In Fig. 1, the dark-field arrangement of a polariscope is shown. The stressed model has a very small thickness compared to its other dimensions. This arrangement reveals the planar real-time stress distribution over the entire observed field of model. As can be seen in Eq. (1), the order of the isochromatics gives the difference of the planar principal stresses. In order to separate the principal stress, an additional equation is required.

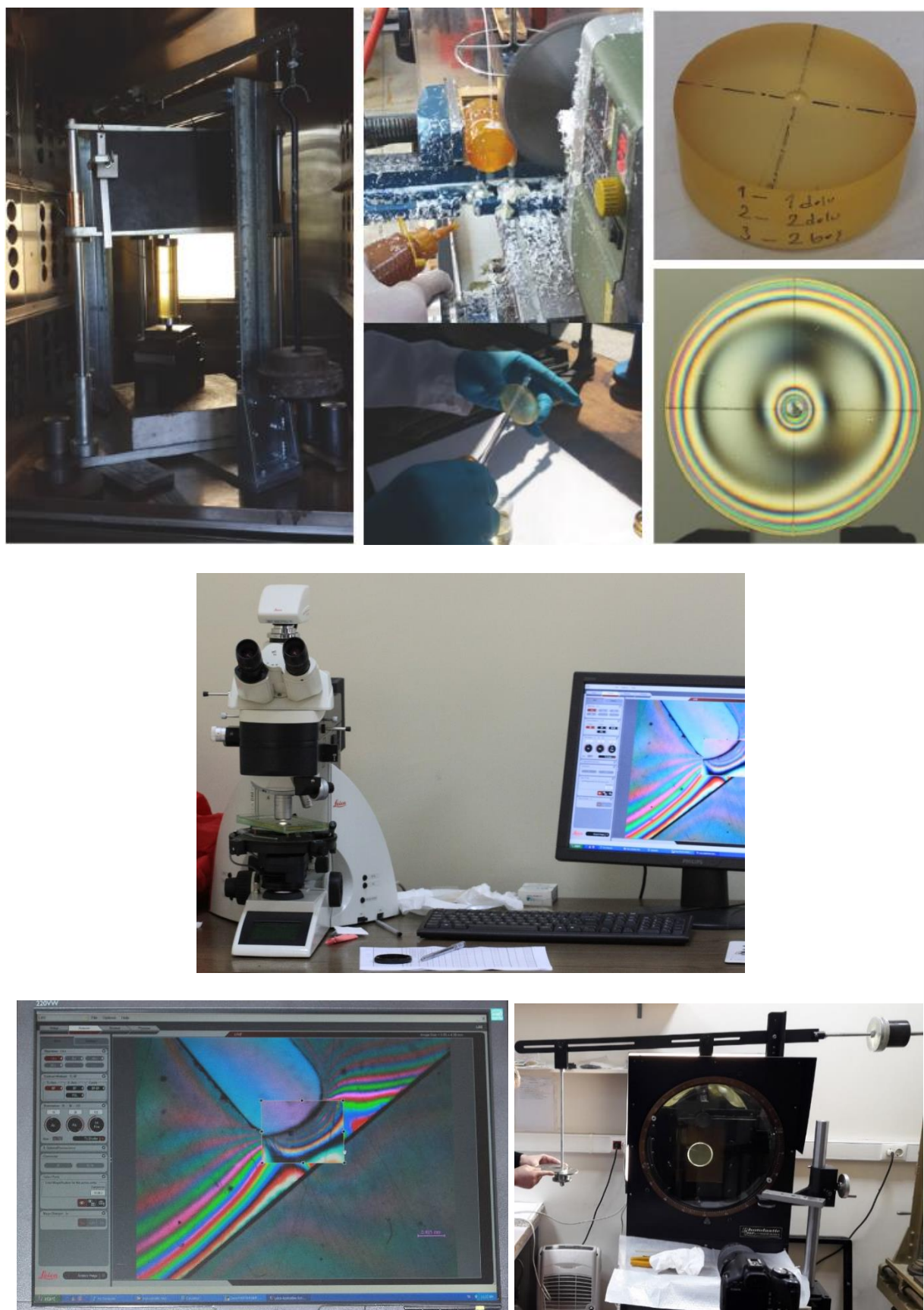


Fig. 2. Real time loading and stress analysis; strain-freezing method and taking slice; the analysis of isochromatics around the tip of cavity using polarized microscope

To derive this, several techniques have been developed in the literature. These can be used to determine the in-plane principle stresses. The directions can also be determined using isoclinic fringe patterns obtained with different arrangements of the polarisation filters. Once the state of stress for the model is determined, one can obtain the state for the prototype. It is known from the theory of elasticity that the stress field does not depend on the material properties if the body forces are neglected. In this respect, the determination of the state of stress is very valuable for the analysis. The stress distribution is related to the linear-elastic deformation. Due to this, the distribution of fringe patterns is recorded using a high-resolution camera. However, the third component of stress cannot be determined with this technique. Therefore, the models in this technique are generally plate-shaped. A 3D analysis is possible with the strain freezing method in the experiments [8-18].

In the strain freezing method, a transparent polymer material, which is linearly elastic at room temperature is heated to a temperature above the glass transition temperature, at which the material behaves linear-elastic with a lower value of the constant modulus of elasticity. The load applied to the model leads to the strain distribution related with this elastic modulus. When this model is gradually cooled, which is necessary to avoid residual stresses in the material due to the temperature change, this strain distribution is fixed in the model. The deformed shape of the model does not change, even if the loads are removed. These deformations are not the result of plastic behavior. The 3D stress analysis can be carried out taking slices from the designated points.

In Fig. 2, a real-time planar loading setup and the application of strain-freezing method are shown. The analysis of isochromatics near a singularity point is difficult and a polarized microscope is used to see the fringe patterns clearly. This microscope has a unit of Berek compensator that is used to measure the phase difference of light components.

In this work, the advantages of the method of photoelasticity are explained using the application examples from the Experimental Mechanics Laboratory at Istanbul Technical University.

2. Determination of the dynamic change in stress at the tip of a cavity. A long plate was axially loaded by a dynamic tensile force (Fig. 3). There were two closed cavities in the centre. The geometries are identical for these cavities. After an initial static load, a dynamic load was applied. A high-speed camera was used for the setup as shown (Fig. 4). The change in the isochromatic fringe distribution was recorded during the dynamic exposure (Fig. 4).

During dynamic loading, the change in the fringes was recorded by a camera. Since the recording rate of the camera and the resolution are low, the video shows the change abruptly. If the capacity of the camera is increased, the dynamic change of the fringes can be clearly visualized. This is intended for the determination of the dynamic stress distribution during crack initiation [17].

3. The stress distribution in underground pipes considering water saturation. The soil-pipe interaction was also investigated using the method of photoelasticity in the Experimental Mechanics Laboratory. For this purpose, a new setup was developed as shown in Fig. 5.

This setup allows a non-intrusive stress analysis without disturbing the soil field. Moreover, water can be added to the system, which increases the saturation of the soil. The pipe is modelled as a plain strain element in these tests.

Different types of soil were tested in this setup to understand the effect of the particle shape. In Fig. 6, two types of soil are given. The geometry of the soil grains are captured with a microscope. As it is seen, the sample on the top has more rounded grains than the sample on the bottom (Fig. 5). In order to understand the effect of the water level in the soil on the stress distribution in the pipe model, the water is manually controlled in the setup. The water level in the soil and the isochromatic fringe distribution in the pipe model are shown in Fig. 6 [11].

4. Conclusion. Photoelasticity is a very powerful method for analysing stress distribution. In this article, some examples of stress analysis performed in the Experimental Mechanics Laboratory in Istanbul Technical University (TU) are presented. There are many such example applications presented in the literature by this laboratory. Especially, some applications focus on the 3D stress analysis. The 3D stress components can be determined using the strain freezing method. The method can be applied to a variety of technical problems in future work. The method is superior to other methods because the entire stress state can be considered in the model. Experimental Mechanics Laboratory is ready to

collaborate on this this type of stress analysis.

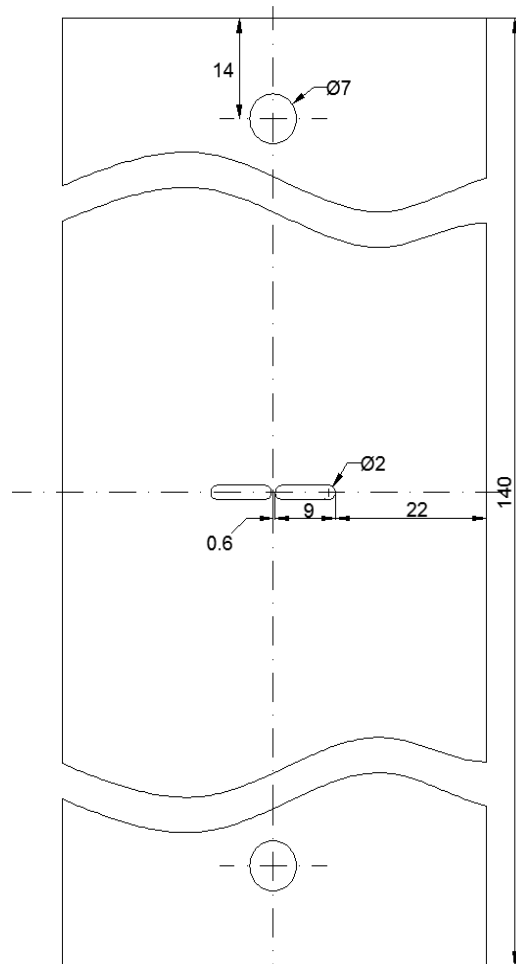
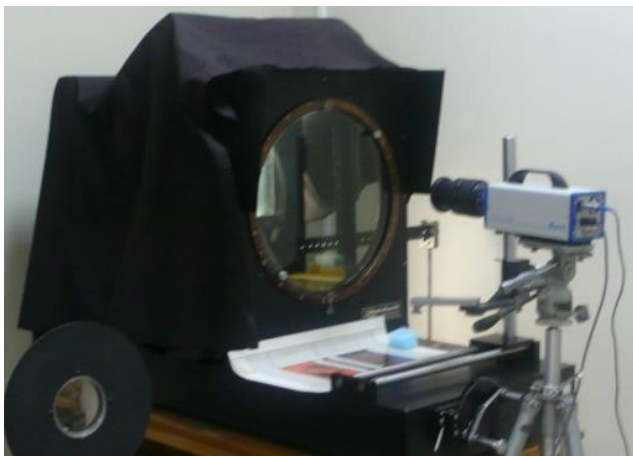
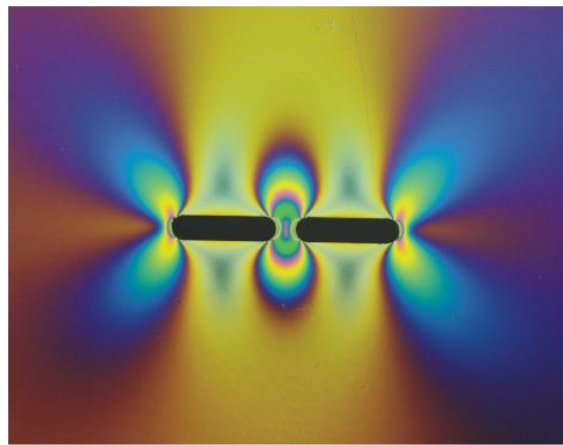


Fig. 3. The sketch of the model



(a)



(b)

Fig. 4. (a) The setup for the dynamic loading, the high-speed camera is utilized to catch the variation of stress concentration around the tips; (b) a picture taken from the model under load, the stress concentrations are seen around the outer tips and the interaction between the cavities are visualized

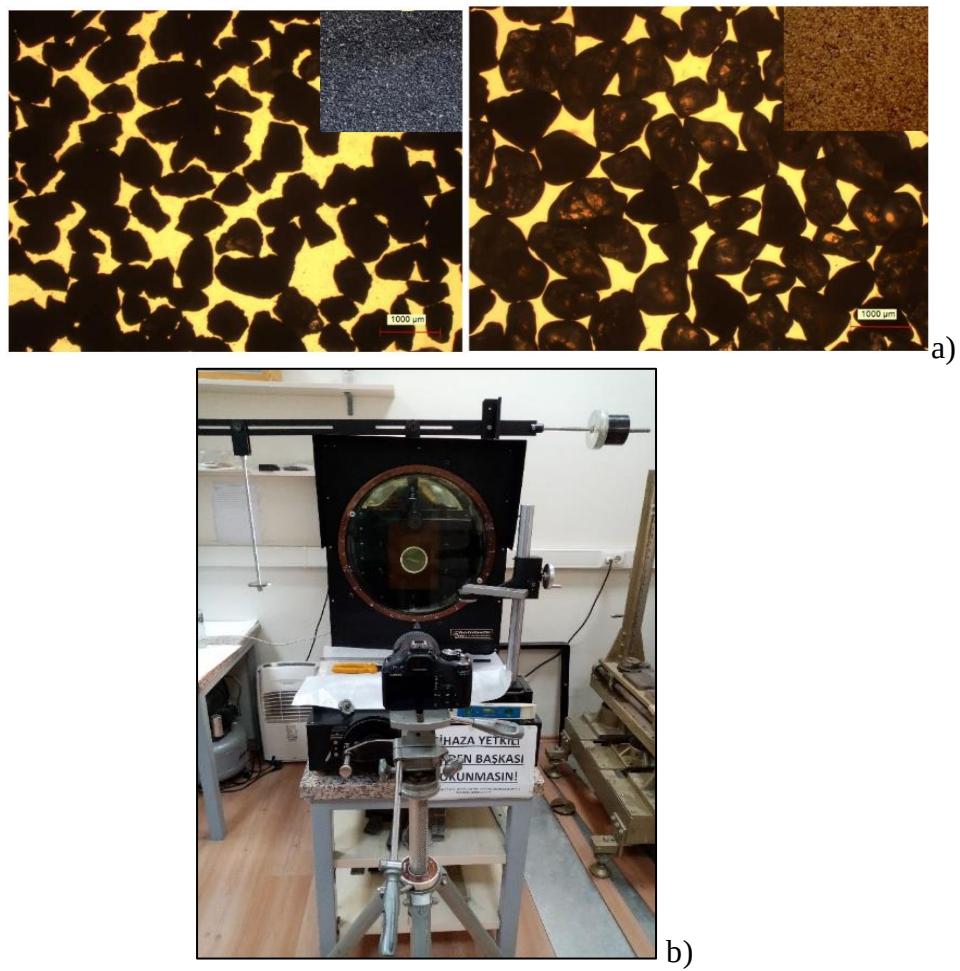


Fig. 5. (a) An original setup for the investigation of stress distribution in a buried pipe, (b) Views of the samples under the polarizing microscope with 16× magnification and with the naked eye

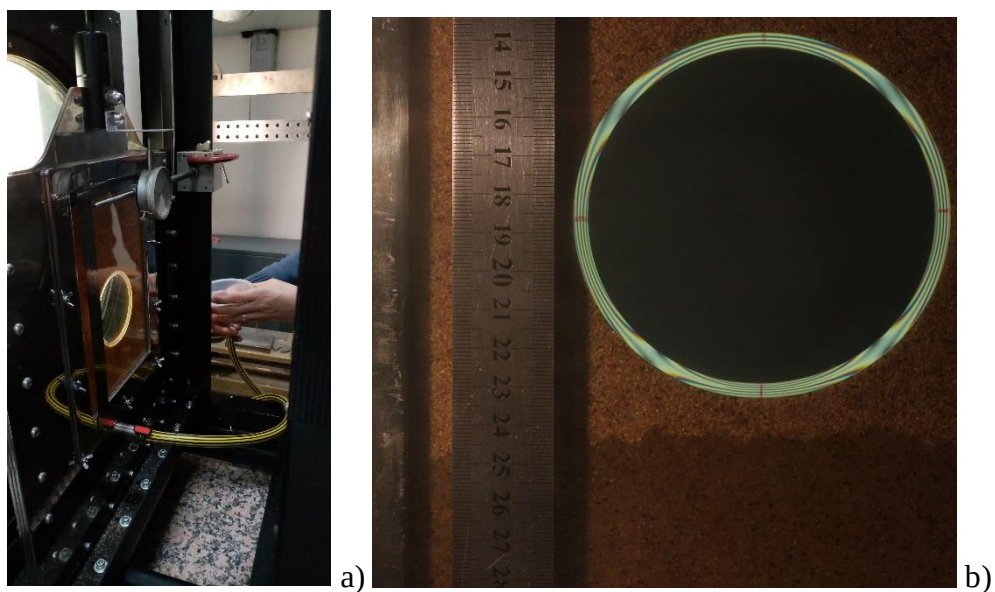


Fig. 6. (a) Changing the water level in the soil field, (b) a stress distribution in the pipe in the model

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Received: 08/09/2025 Accepted: 15/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-53-60>

TEMPERATURE DEPENDENCE OF PHYSICAL AND CHEMICAL PROPERTIES OF ZINC OXIDE DISCOVERED BY RAMAN SPECTROSCOPY

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Abstract. In this work, the phase, optical and structural properties of a ZnO powder sample were studied depending on changes in the annealing temperature. For this, the following main methods were used such as Scanning Electron Microscopy, Raman Spectroscopy, UV-Visible Spectroscopy and Powder Diffractometry-XRD method respectively. The degrees of amorphism and crystallinity were determined using Search Match!3 software. Using Raman spectroscopy, Raman spectroscopy revealed significant changes in the shape, orientation and distribution of peaks of ZnO nanopowders formed with increasing annealing (heating) temperature, as well as to explain the phonon vibration mode. The resulting high Raman intensity confirmed the high-frequency phonon mode of hexagonal wurtzite ZnO. Scanning electron microscopy was used to obtain structural images of the sample.

Keywords: Raman spectroscopy, heterostructures, phonon vibration mode, Raman scattering of light, longitudinal optical - transverse optical frequencies.

1.Introduction. The physical and chemical properties of zinc oxide (ZnO) make it a viable and extremely attractive compound to use in various nanotechnology applications [1-3]. Some of these applications include biomedicine, energy, sensors and optics. As research into ZnO nanostructures continues to grow, it has inspired a number of new innovative applications [4-5]. In addition to its unique chemical properties, it also has simple crystal growth technology and offers significantly lower production costs compared to other semiconductors used in nanotechnology. High-tech devices use new structures created using the latest technologies and modern methods [6-10]. Several processes have been developed to synthesize high-quality ZnO nanostructures, especially in the case of nanowires.

Zinc oxide (ZnO) is a multifunctional group II–VI material due to its wide band gap ($E_g \sim 3.37$ eV) and straight band and with a large exciton binding energy of 60 MeV at room temperature. It also

has the advantages of excellent resistance to radiation damage, suitability for wet etching process, physical and chemical stability, high oxidizing ability, low cost and availability [11-14]. In recent decades, ZnO has become a very promising material used in many fields, such as solar cells, transparent conductive contacts, light-emitting devices, spintronics devices, laser deflectors, paints, antibacterial agents, biosensors, piezoelectric transducers and gas sensors [15-16]. Among these devices and components, many efforts have been made to modify the optical and/or electrical properties of ZnO through doping, ion irradiation, etc. So that it can be more widely used in undoped research areas since raw ZnO is generally inactive in carrier transfer current and is ineffective for the adsorption of solar energy. For example, when ZnO material is applied as a photocatalyst to promote the degradation of organic pollutants, less than 5% of the solar spectrum at the Earth's surface consisting of UV wavelengths can drive the photocatalytic process because the absorption edge is limited by the natural band gap of ZnO. Modification of the band gap of ZnO by metal doping is one of the promising approaches to extend light absorption to the visible wavelength region of light. In addition, these metallic impurities have also demonstrated electron scavenger properties to increase the lifetime of photo-generated electron-hole pairs [17-19].

On the other hand, when ZnO is used for the fabrication of optoelectronic devices, one of the main obstacles for the implementation of optoelectronics based on ZnO devices is the difficulty in achieving high-quality *p*-type ZnO due to the self-compensation effect that occurs due to inherent defects, as well as limited solubility and inactivation of acceptor impurities in the ZnO material. Taking into account the trend towards the creation of nanometer-sized semiconductor devices, the relevance of using optical methods for diagnosing such structures, in particular, the Raman scattering method (RSM), is increasing. In this regard, we identified these phase states for a powder sample at various annealing temperatures from 200⁰C to 700⁰C.

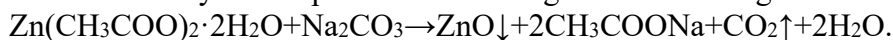
The results of this work, as well as our previous works [27-28], were obtained due to the fact that The Raman spectroscopy method allows and ensures the implementation of qualitative and quantitative analysis of the surface and volume of the sample under study, analysis of the structures of film coatings, registration of defects and stresses in the analyzed structures, control of the phase state of the structures under study, including identification of the amorphous and crystalline phases.

2. Materials and methods. In the present work, an attempt was made to prevent undesirable effects by temperature annealing a ZnO powder sample irradiated at three different temperatures. For this purpose, the following main methods were used, Raman Spectroscopy (Raman) and Powder Diffractometry-XRD, respectively. The degrees of amorphism and crystallinity were determined using Search Match!3 software. Raman spectroscopy and Raman spectroscopy revealed significant changes in the shape, orientation and distribution of peaks of ZnO nanopowders formed with increasing annealing (heating) temperature. The presence of intense Raman scattering of light in ZnO powder samples indicates the existence of a longitudinal optical phonon mode. Small shifts were detected in all ZnO modes, which indicate the presence of stress and strain in the crystal lattice. Changes in particle size were studied using confocal Raman microscopy during temperature annealing. It was shown that changes in the structure and particle size of the material improved its characteristics. It has been confirmed that nanocomposite heterostructures obtained by a simple chemical method are applicable for the creation of optoelectronic devices.

The use of the Raman scattering method, due to the patterns of changes in Raman spectra [20-22], provides a wide range of parameters of the object of study. Raman spectroscopy, or Raman spectroscopy, is applicable to determine the characteristics of research objects as a rapid non-destructive method of analysis, which allows one to estimate the size of nanocrystals from the shape and position of Raman scattering peaks, estimate the ratio of amorphous and crystalline phases, analyze the composition of crystals and evaluate deformations and stresses in crystals [23]. We studied these samples using Raman spectroscopy on an InVia Raman Spectrometer manufactured by Renishaw, UK, when excited by the lines of an RL785 Class 3B Laser laser, with a radiation wavelength of 785 nm. During the measurements, a diffraction grating with a period of 1200 lines/mm was used, and a standard Renishaw CCD Camera detector was used as a recording device [24-26].

JSM-IT210 scanning electron microscopy (SEM) was used to study the morphology of ZnO samples. The composition was analyzed using energy dispersive X-ray (EDX) spectroscopy. The concentrations of chemical elements in the composites were measured using electron probe X-ray spectral microanalyzers for energy dispersive X-ray analysis (EDXA) as part of an SEM.

3.Method of obtaining a sample. Zinc oxide nanoparticles were obtained by precipitation from solution. The synthesis proceeds according to the following scheme:



A 0.1 M solution of Zn (CH₃COO)₂ was added to a 5% solution of polyvinyl alcohol on a magnetic stirrer 30 minutes, then added 0.1 M Na₂CO₃ solution, continued stirring for 15 minutes at room temperature. The resulting precipitate was centrifuged at 3500 rpm and washed with deionized water. They were dried at room temperature.

4.Results and discussion. In this work, the morphological, optical, electrical and structural properties as a function of annealing temperature variation from 200⁰C to 700⁰C were investigated using Raman spectroscopy, UV-visible spectroscopy, and powder diffractometry-XRD, respectively. UV-visible spectroscopy similarly showed that ZnO samples irradiated at different temperatures had band gaps ranging from 3.46 to 3.35 eV. Film resistivity values obtained from current-voltage characteristics showed an exponential increase in resistivity with increasing annealing temperature of the ZnO sample.

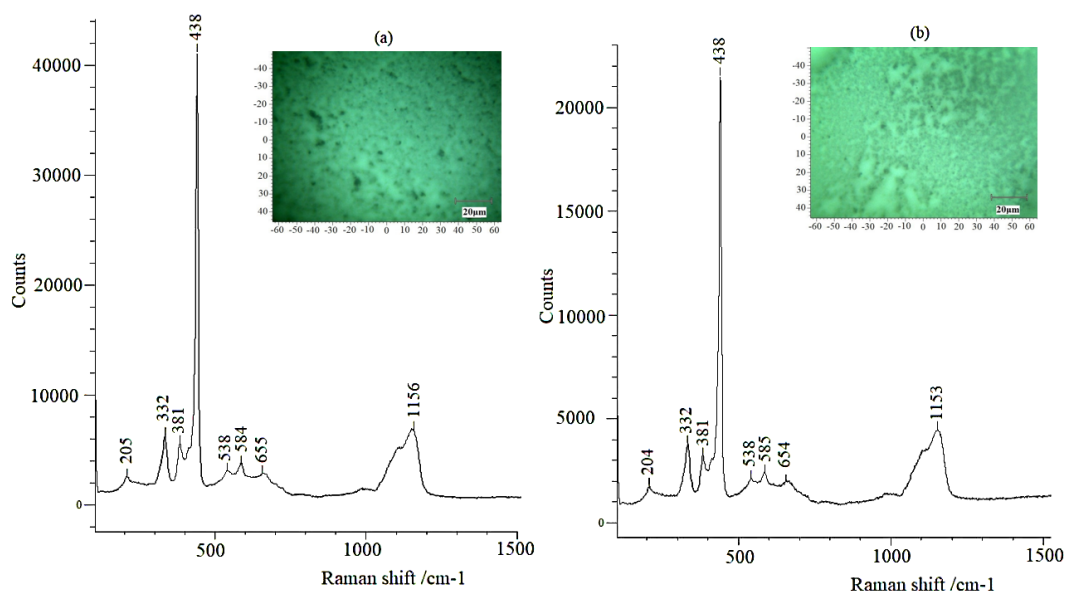


Fig. 1. Raman spectrum of a ZnO sample, as well as an image of a portion of the surfaces of the studied ZnO sample at different annealing temperatures. a) Initial ZnO sample. b) ZnO at annealing temperature $T=200^{\circ}\text{C}$

In figures 1-2. a), b), c), d) the Raman spectra of nanostructures are presented, as well as an image of a portion of the surfaces of the ZnO sample under study. As can be seen from the given data for the initial sample, the intensity of the peak is 438 cm⁻¹ 42000, subsequent annealing at a temperature of 200⁰C leads to a decrease in the intensity of this peak to 24000, and at a temperature of 500⁰C 20000, this suggests that with increasing temperature up to 500⁰C the intensity decreases. At an annealing temperature of 700⁰C, the intensity of this peak sharply increases to 56000.

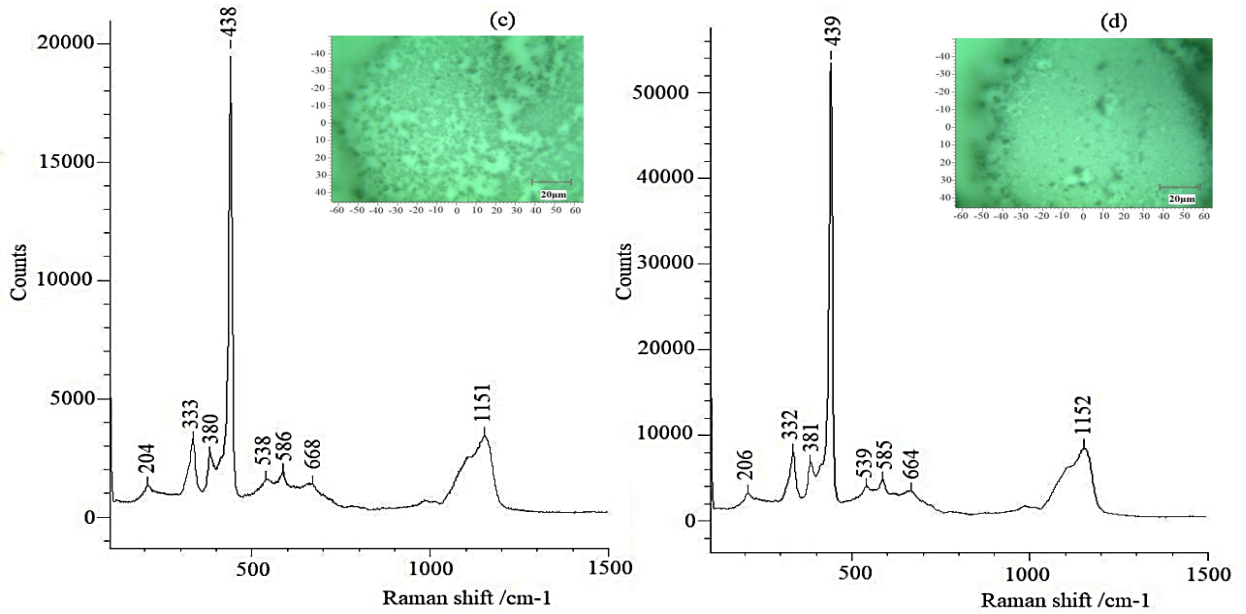


Fig. 2. Raman spectrum of a ZnO sample as well as an image of a section of the surfaces of the studied ZnO sample at different annealing temperatures c) $T=500^{\circ}\text{C}$, d) $T=700^{\circ}\text{C}$

This nature of the growth of this peak suggests that annealing will first lead to the decomposition of the nanolayers, and further annealing will again lead to ordering of the sample structure. The same picture is observed for other peaks of this ZnO material. To make it easier to understand, we have divided the spectra into two parts, from 200 to 510 cm^{-1} and from 530 to 1300 cm^{-1} , as shown in figures 1-2. ZnO peaks at 331, 383 and 436 cm^{-1} were clearly observed. Several peaks at 584, 660, 1101 and 1154 cm^{-1} , respectively, were also detected in the high wavenumber region.

Peaks at 352 and 654 cm^{-1} - A_1 symmetry mode, the peak at 438 cm^{-1} is attributed to non-polar optical phonons of ZnO with a high E_2 mode, and the peak at 381 cm^{-1} corresponds to A_1 symmetry to the frequencies of transverse optical (TO) background modes. Peaks at 585 and 1154 cm^{-1} - E_1 symmetry corresponds to the longitudinal optical modes LO and 2LO, respectively. In addition, the intensities of all observed vibrational modes decrease with increasing annealing temperature to 500 $^{\circ}\text{C}$, and then increase again at an annealing temperature of 700 $^{\circ}\text{C}$. As a result, the size of nanostructures decreases. In addition, their line shapes become asymmetrical.

5. Electron-phonon connection. It is well known that as particle size decreases to the nanoscale or lattice distortion increases, the selection rule $k=0$ for first-order Raman scattering relaxes and phonon scattering will not be limited to the center of the Brillouin zone; therefore, phonon dispersion near the center of the Brillouin zone should also be taken into account. As a result, regimes will be observed, not only shifts and broadening of the optical phonon of the first order scattering mode, but also forbidden symmetry. In this paper, we provide information on electron-phonon coupling from Raman scattering (RS), which has previously been rarely reported for ZnO nanopowders.

The relationship between the second- and first-order scattering cross sections turned out to be very sensitive to the electron-phonon coupling force [23, 24]. For bulk ZnO materials, the intensity ratio E_1 (2LO) and E_1 (LO) was calculated to be 2.85 [25]. This can be clearly observed for the Raman modes E_1 (LO) and E_1 (2LO), respectively. Consequently, as follows from the above, phonon scattering will be limited by the center of the Brillouin zone, the ratio between the second- and first-order Raman scattering cross sections increases. In the wide hump in the range of 560–610 cm^{-1} , lattice vibrations in

$E_1(\text{LO})$ mode in pristine ZnO with peaks at 574 cm^{-1} . E_1 (LO) mode refers to the characteristic of random orientation of ZnO crystallites [27]. This is due to internal defects such as oxygen

vacancies, interstitial Zn and resonance effect in the ZnO lattice crystal at the excitation wavelength [28]. This indicates the presence of a compressive stress effect on the crystal lattice of heterostructural materials. E_1 and A_1 are polar Raman and infrared active because they have LO and TO Raman frequencies. Other ZnO peaks detected at 333, 382, 417–424 and 574 cm^{-1} are assigned to E_2 $H-E_2$ modes L , A_1 (TO), E_1 (TO) and E_1 (LO). These modes exhibit Raman frequency shifts. Moreover, the LO phonon peaks in zinc blende ZnO indicate the existence of a form of heterostructures.

Fig. 3 shows typical examples of SEM images of the surface of ZnO nanopowders. Zinc oxide nanoparticles were obtained by precipitation from sample solutions. From figure 3 it is clear that after temperature annealing, the grain sizes in the ZnO sample vary from a few to several tens of micrometers (figure 3, a, b, c). As mentioned above, the composition was analyzed using energy dispersive X-ray (EDX) spectroscopy.

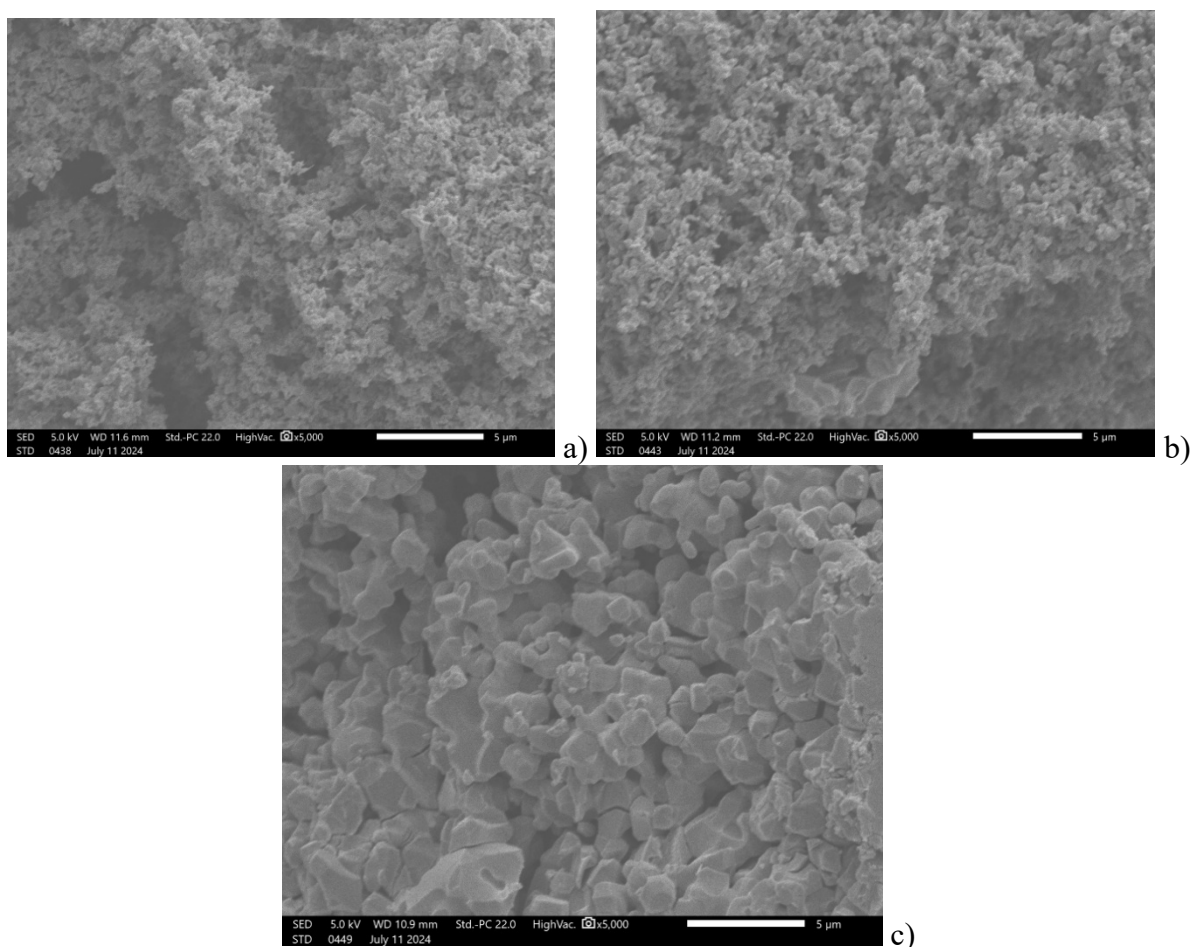


Fig. 3. SEM images of a) the original, b) 700⁰C, c) 1100⁰C surfaces of the ZnO sample under study at different annealing temperatures obtained by scanning electron microscope of the ZnO nanostructure

The atomic ratios of Zn and O in the nanopowders were measured using EDX, and the main results are summarized in figure 3. It is clear that there is an oxygen deficiency for all samples. However, the compositions are approximately maintained within stoichiometry, taking into account the measurement error of the light element oxygen. In addition, we also discovered figure 4(a) the presence of carbon and aluminum in the composition of zinc oxide nanopowder. Despite this, as shown by the results of SEM-EDS analysis, the sample prepared in the above way has pure ZnO phases. X-ray analysis showed that the ZnO samples have a hexagonal ZnO wurtzite structure with peaks at 2θ -positions 31.7°, 34.4°, 36.2°, 47.5°, 56.6° and 62.8° belonging to planes (100), (002), (101), (012),

(110) and (013), respectively, in figure 4 (b). We also determined the Miller indices and lattice parameters. Phase quantitative and qualitative analyzes of ZnO nanopowders were also carried out.

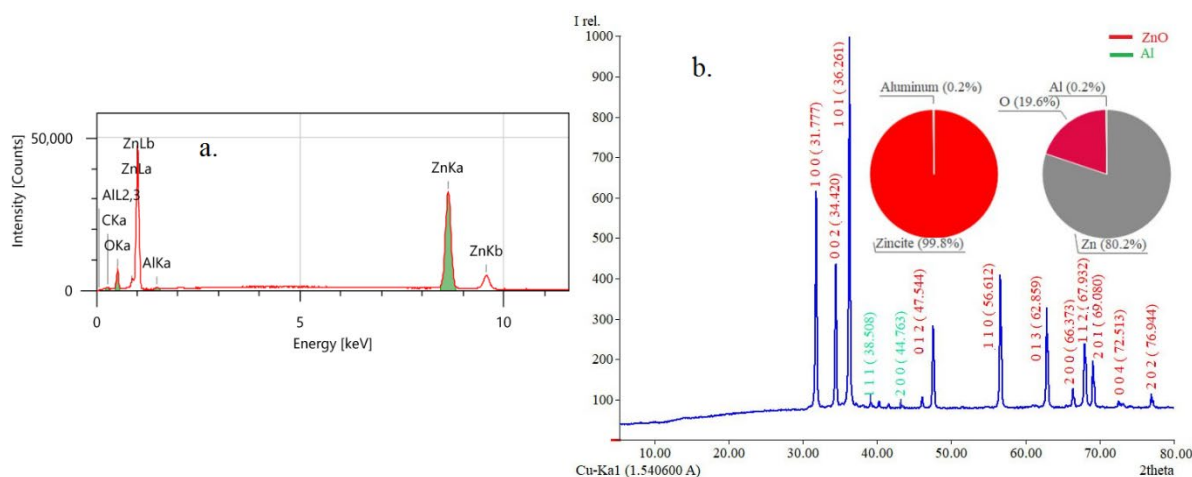


Figure 4. The energy dispersive spectra of the samples obtained from SEM-EDS analysis clearly show that the sample prepared in the above manner has pure ZnO phases (a), X-ray phase analysis of a ZnO sample, Miller indices and lattice parameters (b)

The experimental data obtained are in good agreement with data obtained by other methods. The degree of crystallinity and amorphism of ZnO samples was assessed by X-ray diffraction analysis using the Search and Match!3 program. For zinc oxide, it was found that the amorphous phase is - 86.27% and the crystalline phase is 13.73%, respectively. It was found that with increasing annealing temperature, the crystallinity of the ZnO sample increases slightly.

6.Conclusion. Thus, the Raman spectra of ZnO nanopowders showed that the strength of electron-phonon interaction increases with increasing size of nanocrystals when they are heated to 700°C. The strong $E_2 H$ peak (high-frequency phonons) at 438 cm^{-1} demonstrates the imprint of the hexagonal structure of wurtzite ZnO with good crystallinity. The vibration of the Zn heavy sublattice and the vibration of oxygen are associated with this nonpolar mode. It has relatively higher intensity compared to others, the Raman peak of pristine ZnO is narrow and sharp. Changes in particle size were also detected using confocal Raman microscopy during thermal annealing. It was shown that changes in the structure and particle size of the material improved its characteristics. Oxygen deficiency was also detected for all samples, and the compositions were maintained within stoichiometry, taking into account the measurement error of the light element oxygen. In addition, we determined the presence of carbon and aluminum in the composition of zinc oxide nanopowder.

Competing interests. No competing of interests.

Authors Contributions. Kholikov U.Kh.: Conceptualization, Investigation, Methodology, Data curation. Khozhiev Sh.T.: Validation, Visualization, Writing - original draft. Kosimov I.O.: Formal analysis, Writing - review & editing. Khudaykulov I.Kh.: Formal analysis, Writing - original draft. Berdiyev U.F.: Writing - review & editing, Resources, Supervision. Bekpulatov I.R.: Writing - original draft, Writing - review & editing, Resources, Supervision. Farmonov N.P.: Formal analysis, Writing - review & editing. Gunel Imanova: Formal analysis, Writing - original draft, Writing - review & editing, Supervision.

Funding. Not applicable.

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Received: 16/09/2025 Accepted: 21/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-61-72>

INTEGRATED MODEL FOR ASSESSING THE ENVIRONMENTAL SAFETY OF URBAN WATER SUPPLY AND SEWAGE SYSTEMS

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Abstract. The study presents a systematic approach to improve the environmental safety of urban water supply and sanitation systems through the development of a hierarchical logical-mathematical model. The proposed model combines quantitative and qualitative assessment criteria for classifying the safety status of individual subsystems and the system as a whole. The methodology was tested on the example of a territorial community in south-eastern Ukraine, which made it possible to identify critical infrastructure elements and justify the implementation of technical and organisational measures, in particular, the reconstruction of water supply networks, the modernization of pumping equipment, and the installation of local treatment facilities to ensure compliance with environmental and sanitary standards. The paper proposes a method for integrating blue-green infrastructure elements into urban drainage systems. A multi-level integration scheme, from the household to the district level, has been developed to promote rainwater infiltration, reduce surface runoff, and water pollution. The results of numerical modelling confirm the effectiveness of combined green solutions for improving the environmental performance and sustainability of urban water systems. It has been proven that the implementation of integrated engineering and environmental models is a key factor in the sustainable management of water supply and drainage in conditions of increasing anthropogenic and climatic stress.

Keywords: environmental safety, urban water supply, wastewater disposal, blue-green infrastructure, system modelling, stormwater management, sustainable development of the urban environment

1.Introduction. Research into the issue of ensuring the environmental safety of various urban wastewater disposal systems is one of the priority areas of modern science. Therefore, to formulate the category of ‘environmental safety of urban sewage systems’, we will consider it from the modern perspective of this issue. The term ‘urban wastewater systems’ in this work refers to centralized or decentralized wastewater systems and surface runoff management systems of all forms of ownership that serve individual settlements and/or Amalgamated Territorial Communities (ATCs). The authors [1] define the environmental safety of the state as a concept related to the protection of natural resources and environmental balance, ensuring sustainable economic development, preventing environmental crises, and ensuring an adequate standard of living for the population. We should agree with the opinion of scientists [2] who consider man-made emergencies to be one of the main internal threats to environmental safety in Ukraine. According to open sources, from 1991 to 2023, man-made emergencies accounted for 59% of the total number in Ukraine (Fig. 1).

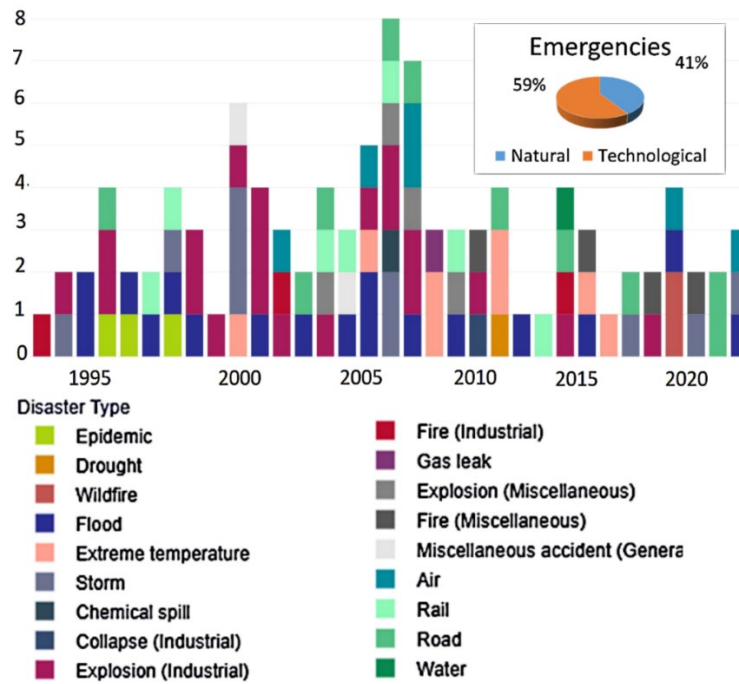


Fig. 1. Emergency situations in Ukraine from 1991 to 2023

The authors [3], focusing on the security aspects of sustainable development, note that environmental security is a key factor in achieving sustainable development, and that the diversity of countries' levels of development in the context of globalisation can lead to exacerbated environmental safety problems and challenges for sustainable development. In his work 'The Economics of Climate Change: The Stern Review,' Stern N. [4], analysing the economic consequences of climate change and their impact on human and property safety, insists on the need for urgent action and notes that the price of inaction exceeds the cost of action. At the same time, the authors [5] argue that the introduction of an environmental accounting system may negatively affect the financial performance of corporations, but will not significantly improve their environmental performance. There should be a positive correlation between environmental performance and the financial results of companies.

Virakun T. et al. [6] propose in their work the application of an interdisciplinary approach to wastewater treatment management to meet the growing demand for safe and clean water in the future. Proskurin O. and colleagues [7] propose to consider the definition of the environmental risk of treatment facilities as the probability of violating the established water quality standards of a water body due to wastewater discharge and to calculate the permissible concentrations of substances in wastewater based on an assessment of the environmental risk caused by the discharge of wastewater into a water body.

Taiwanese scientists [8] assessed the environmental impact based on the EPD 2018 method, using a number of parameters to measure the environmental impact, where the measured environmental indicators were eutrophication, Global Warming Potential over 100 years (GWP100), Biological Oxygen Demand (BOD), and water deficit. Loy-Pilch M. and Zakrzewski A. [9] consider the use of mixed methods, which in turn involves the simultaneous application of quantitative and qualitative methods, to be the most optimal for assessing environmental risk. The authors [10] propose to assess the environmental safety risk of treatment facilities using the Root Cause Analysis (RCA) method, followed by processing the results using the Failure Mode and Effects Analysis (FMEA) method to obtain a Risk Priority Number (RPN). The use of the FMEA method to assess individual risks arising at treatment facilities is also supported by other researchers [11].

Despite the considerable attention and relevance of issues of environmental safety of wastewater systems and the operational reliability of their individual components, the assessment of the environmental safety of urban wastewater systems as a whole remains insufficiently covered in the scientific literature. This also applies to the integration and interaction between water supply and

wastewater systems, which significantly affect the overall efficiency and environmental safety of water resources. Water supply and wastewater systems are closely interrelated. However, in many cases, these systems are analysed and evaluated separately, which can lead to an incomplete understanding of their interaction and insufficiently effective environmental safety management.

The **aim** of this work is to develop a comprehensive approach to assessing and ensuring the environmental safety of urban water supply and wastewater systems by developing an integrated logical mathematical model that takes into account the interrelationships between these systems, allows the identification of potential environmental risks, and justifies effective management and technical solutions to improve the sustainability of water management complexes in urban areas.

2.Methodological principles for assessing the environmental safety of urban water supply and wastewater disposal systems. A scientific approach should be used when developing a strategy to improve the environmental safety of all water supply and sewerage facilities. This approach should take into account a complex set of numerous and unrelated factors that may directly or indirectly affect the lifespan of each element of the system and its performance of relevant sanitary and environmental functions to varying degrees. Therefore, the coordinating vector of the system model should be the use of integrated indicators of the state of the system elements.

To assess environmental safety, a systemic model called the ‘Urban Water Supply and Sewerage System’ (UWSS) is being developed, which uses a structural approach to organizing data and information, allowing complex systems to be systematized. The hierarchical logical-mathematical structure of the Municipal Water Supply and Wastewater System (MWSWS) model is used to classify the safety status of the urban water supply and wastewater disposal system (Fig. 2) and consists of two systems: ‘Municipal Water Supply System’ and ‘Municipal Wastewater Disposal System’.

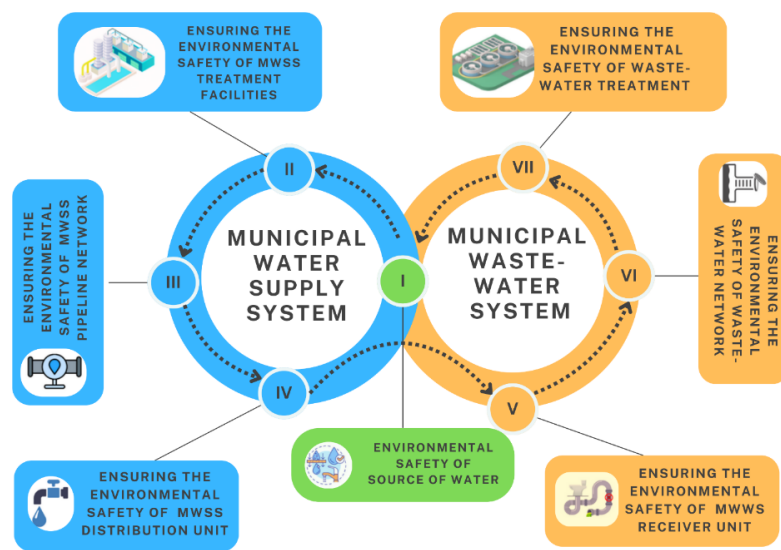


Fig. 2. Block diagram of the model of the ‘Urban Water Supply and Wastewater System’: MWSS – Municipal Water Supply System; MWWS – Municipal Wastewater System

The assessment of the condition of systems and subsystems in the ‘Urban Water Supply and Sewerage System’ model is performed in parallel using two approaches: quantitative and qualitative. A logical function based on a set of qualitative states of individual indicators classifies the qualitative state of the entire system. Quantitative measurement is performed on many states of individual subsystems. The quantitative indicator of the entire system is determined from the quantitative indicators of individual subsystems. The environmental safety of the system is assessed according to the degree of approximation of measures to a specific standard (Fig. 3). Let us consider a step-by-step assessment of the criteria using the example of the ‘Water receiver node’ subsystem.

A step-by-step assessment of the criteria is carried out using the example of the MWWS receiving unit subsystem. The MWWS receiving unit subsystem consists of three units: Chemical

Contamination, Bacteriological Contamination, and Receiver Operation. The 'Receiver Operation' unit is designed to assess the main factors affecting the environmental safety and reliability of internal drainage systems directly at consumers, as well as local treatment facilities located directly at the consumer:

z_1 are physical and design features (pipeline material, service life and wear, and design features);

z_2 are hydraulic features (wastewater flow rate, which is directly related to the water supply schedule, reliability of the consumer's drainage system, and type of the consumer's drainage system);

z_3 are operational features.

The state of the subsystem for each factor is assessed by a set of logical alternatives for the state of the system, which can be represented by a vector: $Z(z_i) = Z_1, Z_2, Z_3$ = 'environmentally safe system', 'conditionally environmentally safe system', 'environmentally unsafe system', the components of which are determined by the following equation:

$$Z(z_i) = \begin{cases} Z_3, & \text{if } z_i < N_1^i \\ Z_2, & \text{if } N_1^i < z_i \leq N_2^i \\ Z_1, & \text{if } z_i > N_3^i \end{cases} \quad i = 1, 2, 3. \quad (1)$$

The standards for this block can be determined based on the reliability index of the drainage system. The main parameters of the reliability of internal drainage systems are the probability of their failure-free operation $P(t)$, the probability that under specified operating conditions, no element will fail within a certain period of time. The parameter $P(t)$ is calculated using the equation:

$$P(t) = \frac{8760 - t_{br}}{8760}, \quad (2)$$

where t_{br} is the duration of interruptions in water supply; $8760 = 24 \cdot 365$ is the number of hours in a calendar year.

To evaluate the aggregated system criterion, the logical measurement function is determined:

$$T_{ij} = \varphi_k(Z) = \begin{cases} -1, & \text{if } Z = Z_3 \\ 0, & \text{if } Z = Z_2 \\ 1, & \text{if } Z = Z_1 \end{cases} \quad k = 1, 2, 3. \quad (3)$$

The assessment of the condition of the 'municipal wastewater drainage receiving unit' is carried out according to the worst value of the indicators of the 'Sewage receiving unit', which informs about the development of a set of measures to improve the reliability of internal networks and plumbing, as well as to improve the environmental safety of wastewater.

The assessment of consumer effluents in terms of chemical pollution is represented by the vector {'environmentally hazardous', 'conditionally environmentally safe', 'environmentally safe'}. These components of the vector are determined by the following logical function:

$$C_s(j_i) = \begin{cases} C_{s3}, & \text{if } j_i > J_0 \\ C_{s2}, & \text{if } J_1 < j_i \leq J_0 \\ C_{s1}, & \text{if } j_i \leq J_1 \end{cases} \quad (4)$$

The assessment of environmental safety for the 'Chemical pollution' block is determined by the following condition:

$$C_s = \max C_s(j_i) \quad (5)$$

The state of the block on the set of classes C_{si} is assessed by the measure $\varphi_r(C_{si})$:

$$\varphi_r(C_{si}) = \begin{cases} -3, & \text{if } C_{si} = C_{s3} \\ -2, & \text{if } C_{si} = C_{s2} \\ 0, & \text{if } C_{si} = C_{s1} \end{cases} \quad r = 1, 2, 3. \quad (6)$$

The assessment algorithm in the 'Bacteriological contamination' block is based on the same principle as in the 'Chemical contamination' block. The graduated levels of the bacteriological contamination criterion determine the situation vector $B_s(w_i)$:

$$B_s(w_i) = \begin{cases} B_{s3}, & \text{if } w_i > W_0 \\ B_{s2}, & \text{if } W_1 < w_i \leq W_0. \\ B_{s1}, & \text{if } w_i \leq W_1 \end{cases} \quad (7)$$

where vector B_s represents a set of alternatives: {‘environmentally hazardous’, ‘conditionally environmentally safe’, ‘environmentally safe’}.

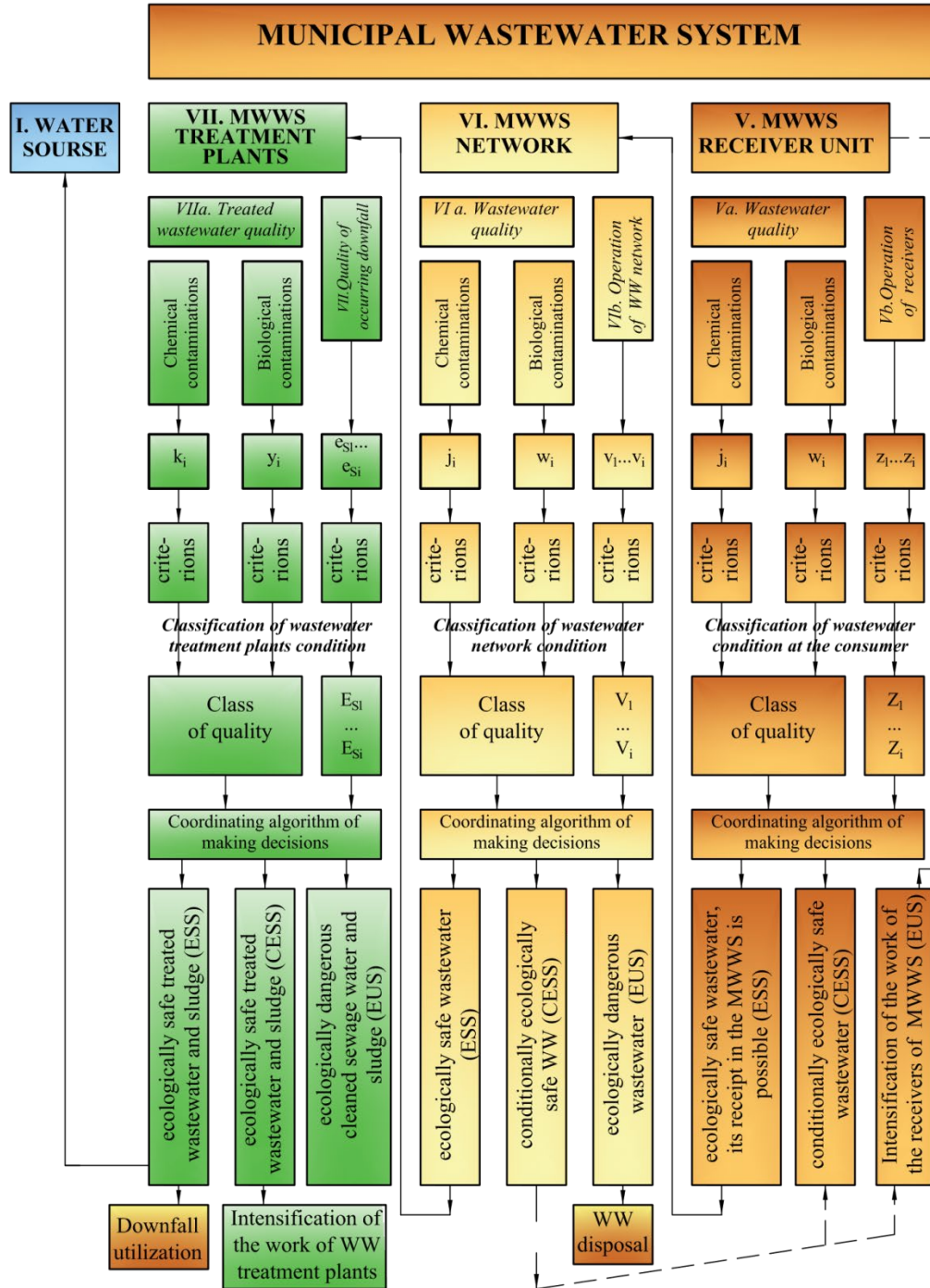


Fig. 3. Structural diagram of the ‘Urban Water Disposal System’ as part of the general logical-mathematical model ‘MWWS’

A numerical measure function is defined on the set of alternatives (8):

$$\varphi_r(B_{si}) = \begin{cases} -3, \text{ if } B_{si} = B_{s3} \\ -1, \text{ if } B_{si} = B_{s2} \\ 0, \text{ if } B_{si} = B_{s1} \end{cases} \quad r = 1, 2, 3 \quad (8)$$

Thus, the quality assessment of wastewater discharged into municipal sewage systems is determined by the following expression (9):

$$C_s B_s = O_s - \operatorname{argmin} \begin{cases} \varphi(C_{si}) \\ \varphi(B_{si}) \end{cases} \quad (9)$$

If the water quality is assessed as ‘conditionally environmentally safe’ or ‘environmentally hazardous’, it is necessary to repeat the calculation, having previously carried out an analysis and intensified the work (or installation) of local treatment facilities at the reception point, based on the maximum pollution indicators. If the assessment is ‘conditionally environmentally safe wastewater,’ it is necessary to analyze the reasons for this situation and take measures to intensify the work of the reception points. After receiving the assessment ‘environmentally safe wastewater,’ the wastewater is sent to the sewerage system. The ‘Sewerage’ and ‘Wastewater Treatment’ subsystems are assessed in a similar manner.

3.Results of the environmental safety assessment of urban water supply and wastewater disposal systems. Figure 4 shows the results of the environmental safety assessment of the urban water supply and wastewater disposal system conducted within the rural united territorial community of south-eastern Ukraine based on the proposed system model. The water supply system of the settlements of the studied amalgamated territorial community showed that they operate in conditions of water supply shortage, and the flow rate of water intake sources and individual wells in the area has decreased during operation. Two alternatives were considered to solve this problem: connection to the existing municipal water supply system and the construction of new wells. Therefore, based on the technical and economic feasibility study, groundwater from new wells located near settlements can be recommended as additional sources of water supply. In addition, it is proposed to reconstruct existing wells and construct new ones, establish sanitary protection zones, and construct reservoirs (measures related to subsystem I).

The quality of water from water supply sources is characterised by an increased salt content. The wear and tear of the water supply network exceeds 50%. The quality of water at the consumer point is unsatisfactory, primarily due to the deterioration of water quality in the system during transportation through worn-out pipelines. Therefore, the following measures are proposed to ensure the comprehensive environmental safety of water supply systems:

- reconstruction of the network;
- replacement of the pumping station's pumping equipment with energy-efficient alternatives (measures relating to subsystem III);
- improvement of the quality indicators of purification at the end of the water treatment process to such an extent that, taking into account the inevitable contamination during transportation, the water at the consumer point meets the established standards: installation of local treatment facilities.

One of the settlements lacks a centralised drainage system and treatment facilities, which has a negative impact on the environmental condition of the area. The existing treatment facilities are in a state of disrepair. During prolonged operation, the wear and tear of building structures causes damage of communications and the structures themselves. Therefore, it is necessary to

- replace the pumping units, electrical cables, and shut-off valves at the sewage pumping stations;
- construct new centralized wastewater disposal systems;
- reconstruct existing networks (measures related to subsystem VI); connect new subscribers (measures related to subsystem V).

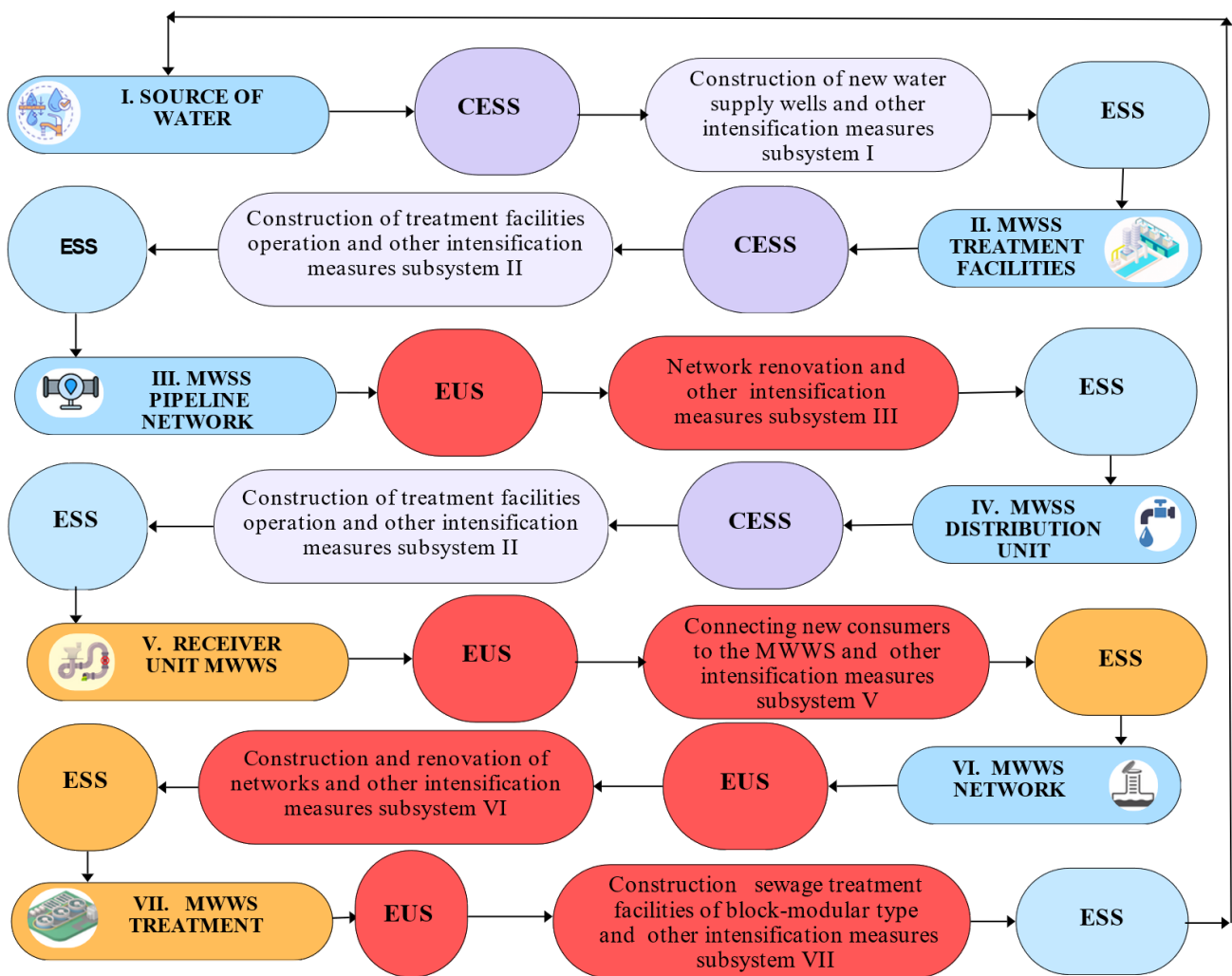


Fig. 4. Structural diagram of the results of the environmental safety assessment of the ‘Urban water supply and sanitation system’: CESS – Conditionally Environmentally Safe System; ESS – Environmentally Safe System; EUS – Environmentally Unsafe System

4.Integration of blue-green infrastructure into the urban drainage system. Issues of environmental safety in cities are closely linked to the effective management of water supply and drainage systems. This area covers a range of issues, including the management of domestic and industrial wastewater, improving the environmental safety of water supply and sewerage facilities, and controlling surface runoff, which plays an important role in minimising negative impacts on aquatic ecosystems and the urban environment. The problem is complicated by the fact that combined sewerage systems, unlike separate ones, collect surface runoff and storm water together with domestic and industrial wastewater before sending it to treatment plants. Such systems consist of a network of pipes used to collect all types of wastewaters simultaneously, which is then transported to treatment plants through a single pipeline system. In dry weather, all effluents are directed to treatment plants. However, during heavy rains or snowmelt, when the volume of wastewater exceeds treatment capacity, the system may direct excess water directly into natural water bodies such as rivers or lakes. If overflow is not possible, untreated wastewater can flood basements and streets, posing a threat to human health and polluting the environment. This phenomenon, known as combined sewer overflows, is one of the main causes of surface water pollution with heavy metals (Cd, Cr, Cu, Ni, Pb, Zn), pathogenic microorganisms, nutrients, pesticides, microplastics, and petroleum hydrocarbons [12].

In addition to traditional strategies for managing urban water supply and wastewater systems, the integration of blue-green infrastructure into the urban environment plays an important role in improving the environmental safety of water supply and sewerage facilities. We propose a blue-green

infrastructure framework for managing surface runoff in urban environments, where the main water retention and drainage elements are permeable pavements and green structures such as rain gardens, green roofs and green walls (Fig. 5). In the urban environment, this infrastructure complements grey drainage systems (sewer networks, reservoirs and treatment plants), providing a comprehensive and balanced approach to managing the overall urban water supply and drainage system.

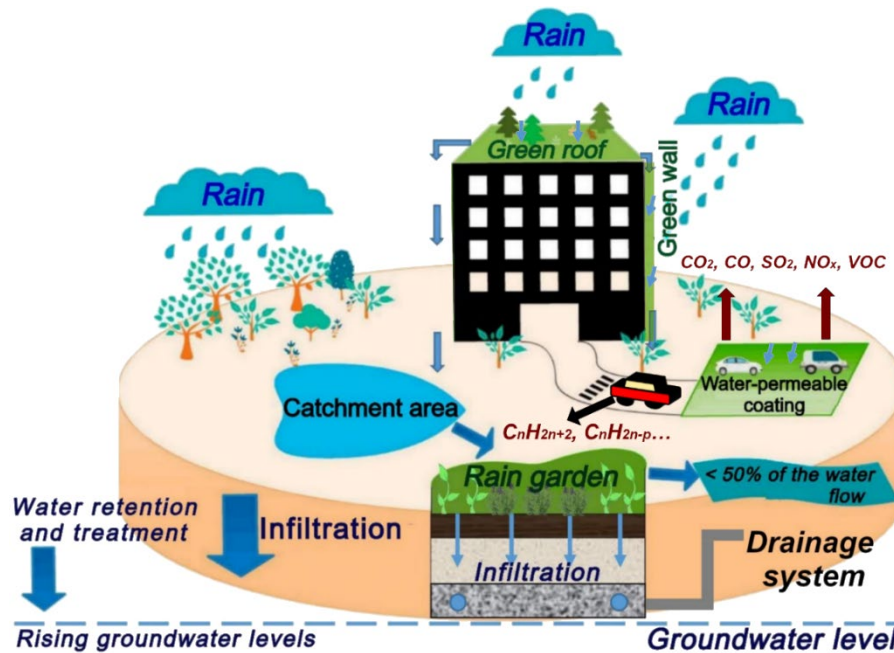


Fig. 5. The principle of blue-green infrastructure in managing surface runoff in urban environments.
Adapted from [13]

The first facilities in the rainwater capture chain in the blue-green infrastructure system are green roofs, which are the first to receive and retain rainwater during a rainfall event. Depending on the intensity and direction of precipitation, some rainwater may fall on green walls, especially during slanting rain. Vertical design, in particular green walls, plays an important role in the selection and design of surface runoff management elements. Since water flow depends on gravity, the location of elements and their relative positioning largely determine how water will pass through the designed system and how it can be treated, stored, or reused.

The remaining water reaches the ground and road surface, forming surface runoff that must be absorbed through green areas, permeable surfaces of eco-friendly parking spaces, roads, pavements, and rain garden structures. In the absence of stormwater sewerage, these structures become the last facilities in surface runoff management, ensuring the retention, filtration, and reduction of the volume of water entering water bodies. Where there are engineering systems, the previous facilities act as the penultimate step in the management, completing the process of absorbing runoff before it is finally discharged into the general sewerage network. Integrated structures of this type improve stormwater infiltration, increase the capacity to retain urban water catchment, and regulate the timing of discharge into the sewerage system, which are key factors for the effective functioning of a city's water supply and sewerage complex.

We propose a method for developing scenarios for integrating blue-green infrastructure into the urban drainage system, consisting of three stages:

1. Identification of infrastructure elements (including types of green structures) and their possible combinations.
2. Calculation of the available area for each element.
3. Forming final scenarios that combine the selected combinations with different implementation rates depending on available resources and priorities.

The first stage involves identifying possible combinations of blue-green infrastructure elements, which include green structures (green roofs, green walls, rain gardens) and engineering solutions such as permeable pavements. These elements can be implemented on different types of land use, such as vegetated surfaces, car parkings, roads, and buildings, maximizing the potential of blue-green infrastructure while minimizing changes in land use and providing multifunctional benefits aimed at improving environmental safety.

In the second stage, the potentially available area for each type of blue-green infrastructure is calculated, taking into account the land use characteristics of the catchment area. Rain gardens are implemented on permeable surfaces, permeable pavements on impermeable surfaces, green roofs on buildings with flat roofs, and green walls on vertical surfaces. Recently, a number of tools have been developed for designing green structures, including rain gardens, using numerical modelling of the hydrological characteristics of the system [14,15]. This includes, in particular, calculating the ratio of the catchment area to the area of the structure, which allows for a more accurate assessment of the effectiveness of runoff management and optimisation of structural parameters to achieve maximum environmental and technical results.

At the final stage, depending on available resources and priorities, possible combinations of blue-green infrastructure elements are generated, taking into account the available area, the wastewater flow system is determined using green structures, and the levels of their integration into the urban infrastructure are established.

The green structure implementation ratio IR_i [%] is determined as the percentage of the corresponding area $A_{sponge,i}$ for a specific type of blue-green infrastructure within the catchment area $A_{basin,i}$ [m²]. Thus, the total surface area of all n types of blue-green infrastructure considered in the scenario is [m²]

$$A_{sponge} = \frac{\sum_{i=1}^n (IR_i \cdot A_{basin,i})}{100}. \quad (10)$$

For each combination of blue-green infrastructure, four possible implementation ratio values are determined: 25 %, 50 %, 75 % and 100 % of the area suitable for a specific type of green structure.

The analysis is conducted at the level of the catchment area, which means that changes in the pace of blue-green infrastructure implementation do not affect its spatial distribution within the sewerage catchment area. For example, implementing blue-green infrastructure on 50 % of the relevant area means that half of this area in each catchment area is covered with green structures, while the overall spatial distribution of the infrastructure remains unchanged.

The characteristics of the surface runoff system play a key role in the ability of combined types of green structures within blue-green infrastructure to influence the efficiency of urban drainage. If the runoff from outside is not directed to the rain garden structure (i.e., the system collects only rainfall that falls directly on it), the effectiveness of combined types is almost the same as that of individual types of blue-green infrastructure, with a difference of 1.2 % to 2.6 % [16]. These minor differences are explained by the greater accuracy of the assessment, which takes into account the simultaneous impact of several elements of blue-green infrastructure.

When runoff is directed from impervious surfaces to a rain garden structure, the combined use of different types of infrastructure provides a significantly greater reduction in runoff volume and improvement in runoff quality compared to the simple sum of the effects of individual elements. This is particularly noticeable when rain gardens are combined with permeable pavements and green roofs. If these elements are assessed separately, runoff from permeable pavements or green surfaces may be counted twice: once as flow to the rain garden and again directly through the assessment of the effectiveness of these structures. This approach can lead to an overestimation of runoff reduction compared to more accurate combined modelling. These aspects highlight the importance of an integrated approach to the use of different types of green structures within an urban catchment, taking into account the characteristics of surface runoff.

The final stage of integrating green structures into the urban drainage system is determining the levels of their integration into the overall urban infrastructure. Green structures within the blue-green infrastructure concept can be integrated into the urban environment as point, linear, or surface systems,

depending on their shape, scale and location. This approach reproduces and supports natural hydrological processes in the urban environment, forming environmental corridors and nodal zones with a linear organisation. Green roofs, green walls and rain gardens play a key role in this, ensuring the infiltration of surface runoff, reducing its volume, and performing a number of environmental, social and economic functions. The basic principle of this system is not only spatial integration, but also a five-level approach to implementation [17]: from local solutions, such as systems for individual buildings or neighbourhoods, to large-scale measures covering residential complexes and districts and integrated into city master plans (Fig. 6).

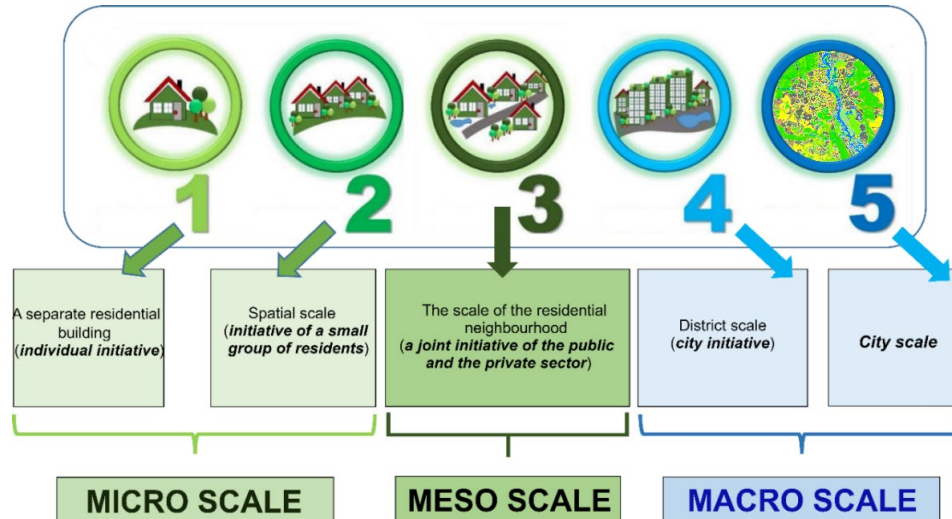


Fig. 6. Levels of integration of green structures into the blue-green infrastructure of the city.
Adapted from [17]

Level 1. Micro scale: individual residential building (individual initiative). At this level, owners of individual residential buildings can implement green structures through simple and effective environmental solutions. Examples of such measures include the creation of rain gardens, green roofs, or green walls, which contribute to local surface runoff purification. Such initiatives not only reduce the load on the urban drainage system, but also have a positive impact on the overall environmental balance of the city.

Level 2. Micro-scale: local spatial level (initiative of a small group of residents). At this level, the implementation of blue-green infrastructure covers larger-scale initiatives organized by small groups of residents. This may include the creation of green areas, rain gardens, or multifunctional public spaces that combine environmental and social functions. Although the scale remains relatively small, such solutions can significantly improve the local environmental situation, increase the efficiency of urban drainage, and contribute to the formation of a sustainable urban environment.

Level 3. Mesoscale: joint initiative of the public and private sectors. At this level, elements of blue-green infrastructure are integrated in the form of linear surface systems. For example, after heavy rain, water flowing from the streets can be collected in underground storage tanks for later use during droughts. Water purified by green structures can be used for landscaping or street washing. This approach creates the basis for a closed or semi-closed water circulation system within the city, which reduces the load on the general sewerage network and promotes the rational use of water resources.

Level 4. Macro scale: district scale (urban initiative). Planning blue-green infrastructure at the district level requires the integration of larger-scale solutions that can affect adjacent areas. The introduction of natural filtration systems in surface residential areas or central areas of the city is particularly relevant.

Level 5. Macro scale: city scale. At the city level, surface runoff management strategies focus on protection from the effects of extreme weather events such as floods or droughts. Engineering solutions include the synergistic interaction of different types of green structures (rain gardens, green

roofs, walls) with technical elements of grey infrastructure. This integration provides a comprehensive solution to urban drainage problems, reducing the risks of natural disasters and promoting the sustainable development of urban areas.

5.Conclusions. The developed systemic model for assessing the environmental safety of urban water supply and wastewater disposal systems allows for a comprehensive analysis of the functional state of all subsystems based on a combination of qualitative and quantitative criteria. The use of a hierarchical logical-mathematical structure makes it possible to classify the state of environmental safety and identify priority areas for system modernization. The results of testing the model on the example of a territorial community in south-eastern Ukraine have proven its effectiveness in identifying critical areas and developing technically and economically sound measures to improve infrastructure reliability, reduce chemical and bacteriological pollution, and ensure sanitary and environmental standards for water supply and wastewater disposal. The integration of blue-green infrastructure into urban wastewater systems is seen as a promising way to improve the environmental safety of urban areas, helping to reduce surface runoff, improve water quality, and create urban ecosystems that are resilient to climate change. The proposed approach can be used in the planning and modernisation of water supply and sewerage systems to achieve a balance between technical efficiency, environmental safety and sustainable development of the urban environment.

Author contributions: Conceptualization, T.T., V.S., M.K., T.K., and V.M.; methodology, T.T. and V.S.; formal analysis, T.T. and V.M.; investigation, V.M.; resources, T.T., V.S., M.K., T.K.; visualization, T.T., M.K., and V.M.; funding T.T., M.K., and V.M.; supervision, T.T. All authors reviewed and approved the final manuscript.

Funding: This research is performed under the support of the Erasmus+ Programme 'Multilevel Local, Nation- and Regionwide Education and Training in Climate Services, Climate Change Adaptation and Mitigation – ClimEd', 619285-EPP-1-2020-1-FI-EPPKA2-CBHE-JP, 15.11.2020 – 14.05.2026.

Conflicts of Interest: The authors declare no conflicts of interest.

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Received: 11/09/2025 Accepted: 11/12/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-73-78>

ON MODIFIED ORLICZ-MORREY SPACES

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Abstract. In this article, we discussed the third version of weak modified Orlicz-Morrey spaces, which is an enlargement of the third version of (strong) modified Orlicz-Morrey spaces. Similar to its first version and second version, the third version of strong and weak modified Orlicz-Morrey space is considered as a generalization of strong and weak Orlicz spaces and strong and weak modified Morrey spaces. This study investigated some properties of the third version modified Orlicz-Morrey spaces. AMS Mathematics Subject Classification: 42B20, 42B25, 42B35; 46E30

Keywords: Orlicz spaces; modified Morrey spaces; modified Orlicz-Morrey spaces; third version

1.Introduction. As is well known, Morrey spaces are widely used to investigate the local behavior of solutions to second order elliptic partial differential equations (PDE). Recall that the classical Morrey spaces $M^{p,\lambda}(R^n)$ and the modified Morrey spaces $\hat{M}^{p,\lambda}(R^n)$ are defined as follows:

$$M^{p,\lambda}(R^n) = \left\{ f \in L^p_{loc}(R^n) : \|f\|_{M^{p,\lambda}} = \sup_{x \in R^n, r > 0} r^{\frac{\lambda}{p}} \|f\|_{L^p(B(x,r))} < \infty \right\}$$

and

$$\hat{M}^{p,\lambda}(R^n) = \left\{ f \in L^p_{loc}(R^n) : \|f\|_{\hat{M}^{p,\lambda}} = \sup_{x \in R^n, r > 0} [r]_1^{\frac{\lambda}{p}} \|f\|_{L^p(B(x,r))} < \infty \right\}$$

respectively, where $[r]_1 = \min\{1, r\}$, $0 \leq \lambda \leq n$, $1 \leq p < \infty$. The space $M^{p,\lambda}(R^n)$ is an extension of the space $L^p(R^n)$ in the sense that $M^{p,0}(R^n) = L^p(R^n)$ and $M^{p,n}(R^n) = L^\infty(R^n)$. Moreover, $\hat{M}^{p,\lambda}(R^n) = M^{p,\lambda}(R^n) \cap L^p(R^n)$, see [1, 4, 5, 6]. Here and everywhere in the sequel, $B(x, r)$ is the ball in R^n of radius r centered at x and $|B(x, r)| = v_n r^n$ is its Lebesgue measure, where v_n is the volume of the unit ball in R^n .

By $WM^{p,\lambda}(R^n)$ and $\widehat{WM}^{p,\lambda}(R^n)$ we denote the weak Morrey space and the weak modified Morrey space defined as the set of functions f in the local weak space $WL^p_{loc}(R^n)$ for which

$$\|f\|_{WM^{p,\lambda}} = \sup_{x \in R^n, r > 0} r^{\frac{\lambda}{p}} \|f\|_{WL^p(B(x,r))} < \infty$$

and

$$\|f\|_{WM^{p,\lambda}} = \sup_{x \in \mathbb{R}^n, r > 0} [r]_1^{\frac{\lambda}{p}} \|f\|_{WL^p(B(x,r))} < \infty$$

respectively, where $\|f\|_{WL^p(B(x,r))} = \sup_{t>0} t \left\{ \left| \{y \in B(x,r) : |f(y)| > t\} \right|^{\frac{1}{p}} \right\}$.

Orlicz spaces are a generalization of Lebesgue spaces L^1 , see [12, 13]. They are useful tools to study harmonic analysis and its applications. For example, the Hardy-Littlewood maximal operator is bounded on L^p for $p > 1$, see [9, 10] and [2] for more precise statements. On the other hand, Morrey spaces was introduced by Ch. B. Morrey to estimate solutions of partial differential equations. After that there are many papers about Morrey spaces. For example, the boundedness of the Hardy-Littlewood maximal operator, fractional integral operators and smoothness properties of solutions of PDE are studied by many mathematicians.

In [3], the generalized Orlicz-Morrey space $M^{\Phi,\varphi}(\mathbb{R}^n)$ was introduced to unify Orlicz spaces and generalized Morrey spaces. Other definitions of generalized Orlicz-Morrey spaces can be found in [11, 14]. In works of [7], generalized Orlicz-Morrey space is the third kind and the ones in [11] and [14] are the first kind and the second kind, respectively. Notice that the definition of the space of the third kind relies only on the fact that $L^\Phi(\mathbb{R}^n)$ is a normed linear space, which is independent of the condition that it is generated by modulars. These spaces are one of the important topics in mathematical analysis, particularly in harmonic analysis. There are three versions of Orlicz-Morrey spaces, i.e: Nakai's, Sawano-Sugano-Tanaka's (Gala et al., 2015) and Deringoz-Guliyev-Samko's (Deringoz et al., 2015) versions.

There are three versions of Orlicz-Morrey spaces. In this article, we focus on the third version of the modified Orlicz-Morrey and the weaker modified Orlicz-Morrey spaces, which extend the third version of the classical Orlicz-Morrey spaces. As in the first and second versions, the third version of the strong and weak Orlicz-Morrey spaces serves as a unifying framework that generalizes the strong and weak Orlicz spaces, the strong and weak Morrey spaces, and their generalized counterparts.

In this manuscript, the authors investigate the third version of weak modified Orlicz-Morrey spaces, which extends the corresponding third version of modified Orlicz-Morrey spaces. Similar to the first and second versions, the third versions of both strong and weak modified Orlicz-Morrey spaces serve as generalizations of the classical strong and weak Orlicz spaces as well as the strong and weak modified Morrey spaces. This study examines several fundamental properties of the third version of modified Orlicz-Morrey spaces.

By $A \lesssim B$ we mean that $A \leq CB$ with some positive constant C independent of appropriate quantities. If $A \lesssim B$ and $B \lesssim A$, we write $A \approx B$ and say that A and B are equivalent.

2 On Young functions and Orlicz spaces. We recall the definition of Young functions.

Definition 2.1. A function $\Phi : [0, \infty) \rightarrow [0, \infty]$ is called a Young function if Φ is convex, left-continuous, $\lim_{r \rightarrow +0} \Phi(r) = \Phi(0) = 0$ and $\lim_{r \rightarrow \infty} \Phi(r) = \infty$.

From the convexity and $\Phi(0) = 0$ it follows that any Young function is increasing. If there exists $s \in (0, \infty)$ such that $\Phi(s) = \infty$, then $\Phi(r) = \infty$ for $r \geq s$. The set of Young functions such that $0 < \Phi(r) < \infty$ for $0 < r < \infty$

will be denoted by $\mathcal{Y}$. If $\Phi \in \mathcal{Y}$, then Φ is absolutely continuous on every closed interval in $[0, \infty)$ and bijective from $[0, \infty)$ to itself. For a Young function Φ and $0 \leq s \leq \infty$, let

$$\Phi^{-1}(s) = \inf \{r \geq 0 : \Phi(r) > s\}.$$

If $\Phi \in \mathcal{Y}$, then Φ^{-1} is the usual inverse function of Φ . We note that

$$\Phi(\Phi^{-1}(r)) \leq r \leq \Phi^{-1}(\Phi(r)) \quad \text{for } 0 \leq r < \infty.$$

It is well known that

$$r \leq \Phi^{-1}(r) \tilde{\Phi}^{-1}(r) \leq 2r \quad \text{for } r \geq 0, \quad (2.1)$$

where $\tilde{\Phi}(r)$ is defined by

$$\tilde{\Phi}(r) = \begin{cases} \sup\{rs - \Phi(s) : s \in [0, \infty)\}, & r \in [0, \infty) \\ \infty, & r = \infty. \end{cases}$$

A Young function Φ is said to satisfy the Δ_2 -condition, denoted also as

$\Phi \in \Delta_2$ if

$$\Phi(2r) \leq C\Phi(r), \quad r > 0$$

for some $C > 1$. If $\Phi \in \Delta_2$, then $\Phi \in Y$. A Young function Φ is said to satisfy the ∇_2 -condition, denoted also by $\Phi \in \nabla_2$, if

$$\Phi(r) \leq \frac{1}{2C} \Phi(kr), \quad r \geq 0,$$

for some $C > 1$.

A Young function Φ is said to satisfy the Δ' -condition, denoted also as

$\Phi \in \Delta'$, if

$$\Phi(tr) \leq C\Phi(t)\Phi(r), \quad t, r > 0$$

for some $C > 1$.

Note that, each element of Δ' -class is also an element of Δ_2 -class.

Remark 2.2. Let $\Phi \in \Delta'$, then we have

$$\Phi(tr) \leq C\Phi(t)\Phi(r), \quad t, r \geq 0.$$

If we set $\Phi(t) = u$ and $\Phi(r) = v$ we get $\Phi(\Phi^{-1}(u)\Phi^{-1}(v)) \leq Cuv \Rightarrow \Phi^{-1}(u)\Phi^{-1}(v) \leq \Phi^{-1}(Cuv) \leq C\Phi^{-1}(uv)$, since $\Phi \in Y$ and Φ^{-1} is concave.

Definition 2.3. (Orlicz Space). For a Young function Φ , the set

$$L^\Phi(R^n) = \left\{ f \in L^1_{loc}(R^n) : \int_{R^n} \Phi(k|f(x)|) dx < \infty \text{ for some } k > 0 \right\}$$

is called Orlicz space. If $\Phi(r) = r^p$, $1 \leq p < \infty$, then $L^\Phi(R^n) = L^p(R^n)$. If $\Phi(r) = 0$, $(0 \leq r \leq 1)$ and $\Phi(r) = \infty$, $(r > 1)$, then $L^\Phi(R^n) = L^\infty(R^n)$. The space $L^\Phi_{loc}(R^n)$ is defined as the set of all functions f such that $f\chi_B \in L^\Phi(R^n)$ for all balls $B \subset R^n$. $L^\Phi(R^n)$ is a Banach space with respect to the norm

$$\|f\|_{L^\Phi} = \inf \left\{ \lambda > 0 : \int_{R^n} \Phi\left(\frac{|f(x)|}{\lambda}\right) dx \leq 1 \right\}.$$

We note that

$$\int_{R^n} \Phi\left(\frac{|f(x)|}{\|f\|_{L^\Phi}}\right) dx \leq 1 \quad (2.2)$$

Lemma 2.4. [3] For a Young function Φ and $B = B(x, r)$, the following inequality is valid

$$\|f\|_{L^1(B)} \leq 2|B| \Phi^{-1}(|B|^{-1}) \|f\|_{L^\Phi(B)}.$$

Definition 2.5. Let Φ be a Young function. The weak Orlicz space is defined as

$$WL^\Phi(R^n) := \left\{ f \in L^1_{loc}(R^n) : \|f\|_{WL^\Phi} < \infty \right\},$$

where

$$\|f\|_{WL^\Phi} = \inf \left\{ \lambda > 0 : \sup_{t>0} \Phi\left(\frac{t}{\lambda}\right) d_f(t) \leq 1 \right\},$$

and $d_f(t) = \left| \left\{ x \in R^n : |f(x)| > t \right\} \right|$.

Lemma 2.6. If $0 < \|f\|_{WL^\Phi} < \infty$, then

$$\sup_{t>0} \Phi\left(\frac{t}{\|f\|_{WL^\Phi}}\right) d_f(t) \leq 1. \quad (2.3)$$

Proof. By the definition of $\|\cdot\|_{WL^\Phi}$, for all $\lambda > \|f\|_{WL^\Phi}$ we have $\Phi\left(\frac{t}{\lambda}\right) d_f(t) \leq 1, \forall t > 0$. Now as λ decreases to $\|f\|_{WL^\Phi}$, the quotient $\frac{t}{\lambda}$ increases to $\frac{t}{\|f\|_{WL^\Phi}}$. By the left-continuity of Φ , we have

$\Phi\left(\frac{t}{\lambda}\right) \uparrow \Phi\left(\frac{t}{\|f\|_{WL^\Phi}}\right)$. Therefore we get the desired result. By elementary calculations we have the following.

Lemma 2.7. Let Φ be a Young function and B a set in R^n with finite Lebesgue measure. Then

$$\|\chi_B\|_{L^\Phi} = \|\chi_B\|_{WL^\Phi} = \frac{1}{\Phi^{-1}(|B|^{-1})}.$$

The following theorem is an analogue of the Lebesgue differentiation theorem in Orlicz spaces.

Theorem 2.8. [8] Suppose that Φ is a Young function and let $f \in L^\Phi(R^n)$ be nonnegative. Then

$$\liminf_{r \rightarrow 0+} \frac{\|f\chi_{B(x,r)}\|_{L^\Phi}}{\|\chi_{B(x,r)}\|_{L^\Phi}} \geq f(x), \quad \text{for almost every } x \in R^n.$$

If we moreover assume that $\Phi \in \Delta'$, then

$$\liminf_{r \rightarrow 0+} \frac{\|f\chi_{B(x,r)}\|_{L^\Phi}}{\|\chi_{B(x,r)}\|_{L^\Phi}} = f(x), \quad \text{for almost every } x \in R^n.$$

3 Modified Orlicz-Morrey Spaces

Definition 3.1. For a Young function Φ and $\lambda \in R$, we denote by $M^{\Phi,\lambda}(R^n)$ the Orlicz-Morrey space, defined as the space of all functions $f \in L_{loc}^\Phi(R^n)$ with finite quasinorm

$$\|f\|_{M^{\Phi,\lambda}} = \sup_{x \in R^n, r>0} \Phi^{-1}(r^{-\lambda}) \|f\chi_{B(x,r)}\|_{L^\Phi}.$$

Note that $M^{\Phi,\lambda}(R^n)_{\lambda=0} = L^\Phi(R^n)$ and $M^{\Phi,\lambda}(R^n)_{\Phi(t)=t^p} = M^{p,\lambda}(R^n)$.

Definition 3.2. For a Young function Φ and $\lambda \in R$, we denote by $\widehat{M}^{\Phi,\lambda}(R^n)$ the modified Orlicz-Morrey space, defined as the space of all functions $f \in L_{loc}^\Phi(R^n)$ with finite quasinorm

$$\|f\|_{\widehat{M}^{\Phi,\lambda}} = \sup_{x \in R^n, r>0} \Phi^{-1}([r]_1^{-\lambda}) \|f\chi_{B(x,r)}\|_{L^\Phi}.$$

Note that $\widehat{M}^{\Phi,\lambda}(R^n)_{\lambda=0} = L^\Phi(R^n)$ and $\widehat{M}^{\Phi,\lambda}(R^n)_{\Phi(t)=t^p} = \widehat{M}^{p,\lambda}(R^n)$.

Definition 3.3. For a Young function Φ and $\lambda \in R$, we denote by $WM^{\Phi,\lambda}(R^n)$ the weak Orlicz-Morrey space, defined as the space of all functions $f \in WL_{loc}^\Phi(R^n)$ with finite quasinorm

$$\|f\|_{WM^{\Phi,\lambda}} = \sup_{x \in R^n, r>0} \Phi^{-1}\left(|B(x,r)|^{-\frac{\lambda}{n}}\right) \|f\chi_{B(x,r)}\|_{WL^\Phi}.$$

Definition 3.4. For a Young function Φ and $\lambda \in R$, we denote by $LM^{\Phi,\lambda}(R^n)$ the local

Orlicz-Morrey space, defined as the space of all functions $f \in L_{loc}^\Phi(R^n)$ with finite quasinorm

$$\|f\|_{LM^{\Phi,\lambda}} = \sup_{r>0} \Phi^{-1}(r^{-n}) \|f\chi_{B(0,r)}\|_{L^\Phi}.$$

Note that $LM^{\Phi,\lambda}(R^n)|_{\lambda=0} = L^\Phi(R^n)$ and $LM^{\Phi,\lambda}(R^n)|_{\Phi(t)=t^p} = LM^{p,\lambda}(R^n)$.

The following statement is true.

Lemma 3.5. If $\Phi \in \Delta'$, then $\hat{M}^{\Phi,n}(R^n) = L^\Phi(R^n) \cap L^\infty(R^n)$ and

$$\|f\|_{\hat{M}^{\Phi,n}} \approx \max\{\|f\|_{L^\infty}, \|f\|_{L^\Phi}\}$$

Proof. Let $f \in L^\Phi(R^n) \cap L^\infty(R^n)$. Then

$$\begin{aligned} \|f\|_{\hat{M}^{\Phi,n}} &= \sup_{x \in R^n, r>0} \Phi^{-1}([r]^{-n}) \|f\chi_{B(x,r)}\|_{L^\Phi} = \max\left\{ \sup_{x \in R^n, 0<r \leq 1} \Phi^{-1}([r]^{-n}) \|f\chi_{B(x,r)}\|_{L^\Phi}, \sup_{x \in R^n, r>1} \Phi^{-1}([r]^{-n}) \|f\chi_{B(x,r)}\|_{L^\Phi} \right\} \\ &= \max\left\{ \sup_{x \in R^n, 0<r \leq 1} \Phi^{-1}(r^{-n}) \|f\chi_{B(x,r)}\|_{L^\Phi}, \Phi^{-1}(1) \sup_{x \in R^n, r>1} \|f\chi_{B(x,r)}\|_{L^\Phi} \right\} \\ &\leq \max\left\{ \|f\|_{L^\infty} \sup_{x \in R^n, 0<r \leq 1} \Phi^{-1}(r^{-n}) \chi_{B(x,r)}\|_{L^\Phi}, \Phi^{-1}(1) \|f\|_{L^\Phi} \right\} \\ &\lesssim \max\{\|f\|_{L^\infty}, \|f\|_{L^\Phi}\}, \end{aligned}$$

which implies $\|f\|_{\hat{M}^{\Phi,n}} \lesssim \max\{\|f\|_{L^\infty}, \|f\|_{L^\Phi}\}$.

Now let $f \in \hat{M}^{\Phi,n}(R^n)$. Theorem 2.8 implies that $|f(x)| \leq \|f\|_{\hat{M}^{\Phi,n}}$ for almost every $x \in R^n$, which means that $\|f\|_{\hat{M}^{\Phi,n}} \geq \|f\|_{L^\infty}$. It also follows from the definition of modified Orlicz-Morrey spaces that $\|f\|_{L^\Phi} \leq \|f\|_{\hat{M}^{\Phi,n}}$.

Therefore,

$$\max\{\|f\|_{L^\infty}, \|f\|_{L^\Phi}\} \leq \|f\|_{\hat{M}^{\Phi,n}}.$$

In the following we denote by Θ the set of all functions equivalent to 0 on R^n .

Lemma 3.6. Let Φ be a Young function. If $\lambda < 0$ or $\lambda > n$ and $\Phi \in \Delta'$, then $M^{\Phi,\lambda}(R^n) = \Theta$.

Proof. First let $\lambda < 0$ and $f \in M^{\Phi,\lambda}(R^n)$. For all $x \in R^n$ and $r > 0$ we have

$$\|f\chi_{B(0,r)}\|_{L^\Phi} \leq \frac{\|f\|_{M^{\Phi,\lambda}}}{\Phi^{-1}(r^{-\lambda})},$$

which implies that $\|f\|_{L^\Phi} = \lim_{r \rightarrow \infty} \|f\chi_{B(x,r)}\|_{L^\Phi} = 0 \Rightarrow f(x) = 0$, for almost every $x \in R^n$, since $\lim_{r \rightarrow \infty} \Phi^{-1}(r) = \infty$.

Now let $\lambda > n$ and $f \in M^{\Phi,\lambda}(R^n)$. For all $x \in R^n$ and $r > 0$ we have from Remark 2.2 and Theorem 2.8

$$\frac{\|f\chi_{B(x,r)}\|_{L^\Phi}}{\|\chi_{B(x,r)}\|_{L^\Phi}} \leq \frac{\Phi^{-1}(r^{-n})}{\Phi^{-1}(r^{-n}r^{n-\lambda})} \|f\|_{M^{\Phi,\lambda}} \leq \frac{\|f\|_{M^{\Phi,\lambda}}}{\Phi^{-1}(r^{n-\lambda})},$$

which implies that $|f(x)| = 0$, for almost every $x \in R^n$.

Remark 3.7. In the case $\Phi(t) = t^p$, for $1 \leq p < \infty$ from Lemmas 3.5 and 3.6 we get the following well-known results: $M^{p,n}(R^n) = L^\infty(R^n)$ and $\hat{M}^{p,\lambda}(R^n) = \Theta$ for $\lambda < 0$ or $\lambda > n$.

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Received: 01/09/2025 Accepted: 16/12/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-79-84>

AN EFFECTIVE MODEL FOR TRAINING SPECIALISTS IN TRANSPORT CONSTRUCTION: A CASE STUDY ON THE BASE DEPARTMENT OF JSC “MOSTOSTROY-11”

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Abstract. This article addresses the problem of training managerial and engineering personnel for the transport construction industry in Russia. It highlights a systemic personnel crisis, the aging of academic staff, and the lack of interest among young people in academic careers. The classical higher education system, for all its merits, often fails to keep pace with the dynamics of business, creating a painful gap between the theory taught in classrooms and the practice prevailing at construction sites and design institutes. A university graduate joining an enterprise faces the need for lengthy and costly adaptation: they must relearn, master current software, immerse themselves in the company's internal standards, and understand the logic of real-world, rather than academic, construction and business processes. The article describes the successful experience of cooperation between a higher education institution and the transport construction industry, implemented at the Tyumen Industrial University, where an effective model for training specialists in transport construction, focused on the real needs of the industry, has been created. This is a full-fledged public-private partnership, where the company acts as a co-author and active participant in training its future employees at all stages. The universality of the principles embedded in this model—continuity of the educational path (from schools to university), practice-oriented approach, direct employer involvement in the educational process, and the use of real cases and technologies—makes it an effective template for replication in other sectors of the economy: oil and gas, mechanical engineering, energy, and the IT sector.

Keywords: personnel training, transport construction, specialist training model, base department, industry-university partnership, practical training, JSC "Mostostroy-11".

1.Introduction. The primary mission of an engineer in transport construction in our material world is to ensure the reliability of constructed facilities and their sufficient resilience to numerous natural and artificial factors. However, this must be achieved with minimal expenditure of time, labor, materials, and energy in short, with maximum cost savings. It is not so difficult to build one small structure so that it does not collapse; the challenge is to build many such structures. Any over expenditure of materials, any excessive safety margins or inefficiencies, which might sometimes be acceptable for unique structures, are detrimental in the context of mass construction, as they can negate its entire purpose. In other words, economical, rational, and comprehensively justified solutions allow for the accumulation of sufficient capital to invest in mass construction. And it is the engineer who plays the leading role here. Only they can prove that a given structure possesses the necessary reliability at a specific level of economy, that precisely this amount of material is required, and that these specific methods should be used to erect the structure to protect this creation of human hands from various real or potential dangers.

Yet, despite its importance and necessity, mass construction cannot be the true field of activity for an engineer. The true field for an engineer, the area where their talent is manifested, where they can

apply all their knowledge and imagination, is unique structures. These are bridges spanning hundreds of meters, even several kilometers, without intermediate supports. The invisible conflict between the forces of gravity and the structure, which is less acute in conventional construction, reaches its climax here. Internal forces strive to break the connections within the structure, to destroy the material from which it is made. And only a skilled engineer can correctly proportion the quantity, form, and structure of the material so that the structure ultimately emerges victorious from any confrontation with the blind forces of nature and remains victorious throughout its entire service life.

Natural disasters and various emergency situations rarely occur in properly designed, constructed, and maintained structures; in some fortunate cases, they may not occur at all during the structure's existence. But this does not mean the structure is at rest under these conditions. On the contrary! Every structure is subjected daily, hourly, throughout its life, to "service" loads, which are inevitable for it. These loads acting on the structure have a natural tendency to move downwards along the most direct path vertically, which in ordinary language means collapse, catastrophe. Only a rational and expedient structure restrains this catastrophic downward tendency, and this struggle between the structure and the loads continues tirelessly for days, years, and, if fortunate, centuries. One could say that the structure is a perpetually tensed muscle that must be indefatigable. It is easy to imagine what would happen if this muscle, holding thousands of tons, were to tire and relax. Of course, under normal conditions, this muscle the structure is not maximally stressed. This is logical, as it must conserve strength for emergency, particularly severe conditions. Under normal operational conditions, the primary acting force is the mass of the structure itself and the useful load for which it was built (in the case of a bridge, this is the live load: cars, trains). Stresses in this case are significantly lower than the ultimate strength capabilities of the material. The load-bearing system of the structure responds to the increase and decrease of loads with peculiar ebbs and flows of stresses in its elements. At a certain moment, all loads may act on the structure simultaneously, causing stresses to rise sharply, and the structural muscle finds itself in a dangerously stressed state. It is strained to the extreme, with the material working at the limit of its capabilities. Will the engineer be able to foresee such a severe, yet quite realistic situation, which could be critical for a given element or node of the structure? They must. They must foresee everything. They must foresee not only all possible impacts on the future bridge structure but also all possible combinations of individual impacts. And not only foresee them but also provide as accurate a quantitative assessment as possible.

Now, let us turn to the problem of training the qualified engineers the country needs. Unfortunately, the modern transport construction industry in Russia is facing a systemic personnel crisis, manifested both in an acute shortage of qualified bridge engineers and a deficit of academic staff capable of training such specialists [1-7]. This problem is one of the most acute and systemic for the country's infrastructure development, as it directly threatens the implementation of large-scale national projects related to the expansion and modernization of the transport network. An analysis of the state of higher education shows that personnel training for bridge construction is concentrated in a limited number of universities, with many regions of the country lacking specialized graduating departments. The situation is exacerbated by the absence of a coordinated state policy in road and bridge education, weak funding for research and teaching activities, low salary levels for faculty, and high teaching loads that leave no time for scientific work [4,6]. As a result, university graduating departments are aging, young people are not striving for academic careers, and employers face difficulties in attracting competent specialists. Thus, the gap between the needs of a dynamically developing industry and the capabilities of the education system is becoming critical, which determines the high relevance of finding effective solutions.

In these conditions, the experience of successful cooperation between universities and the transport construction industry, implemented at the base department of JSC "Mostostroy-11" at the Tyumen Industrial University, where an effective model for training specialists in transport construction, focused on the real needs of the industry, has been created, is of particular relevance.

2.The problem: systemic personnel crisis and the gap between education and practice.

Modern transport infrastructure (multi-kilometer bridges, complex interchanges, high-speed highways) is not only a symbol of a state's technological progress but also its strategic economic asset. Behind

every created object lies the colossal work of engineers, designers, technologists, and managers. It is human capital, not just concrete and metal, that becomes the key resource in global competition. And here, the transport construction industry faces a systemic challenge: an acute shortage of personnel ready to work in the realities of complex, high-tech projects. The classical higher education system, for all its merits, often fails to keep pace with the dynamics of business, creating a painful gap between the theory taught in classrooms and the practice prevailing at construction sites and design institutes [3,5,7,9].

A university graduate joining an enterprise faces the need for lengthy and costly adaptation. They must relearn: master current software, immerse themselves in the company's internal standards, and understand the logic of real-world, rather than academic, construction and business processes. For the enterprise, these are direct economic costs: the time of experienced mentors, slowdown of work processes, and the risk of errors. For the young specialist, it is stress, loss of motivation, and, often, disillusionment with the chosen profession. This problem is systemic and requires a systemic, strategic approach to solve it.

The problem is further intensified by the widespread digital transformation, where project efficiency directly depends on proficiency with advanced digital tools and neural network technologies, requiring graduates to possess competencies that meet the level of modern technological challenges.

3. The solution: an integrated base department model as a bridge between university and industry. One effective response to this problem can be a model of deep integration of large business into the educational process. An example of the successful implementation of such a strategy is the experience of one of Russia's leading infrastructure companies, JSC "Mostostroy-11" (part of the infrastructure holding JSC "Group of Companies 'Natsproektstroy'"), in creating, supporting, and developing a base department at the Tyumen Industrial University (TIU). This is not sponsorship or one-off master classes, but a full-fledged public-private partnership, where the company acts as a co-author and active participant in training its future employees at all stages.

3.1. A continuous path from the school classroom to the engineering workshop. The general concept of the project is based on the principle of educational continuity. It is obvious that fostering a loyal and motivated specialist should begin long before they become an applicant. The work starts with career guidance in target schools. In our case, the partnership includes specialized classes at the MBOU OO "Isilkul Lyceum" (annual graduation of 25-30 people), MAOU Secondary School No. 88 in Tyumen (annual graduation of 30-35 people), and a networked "Mostostroy-Class" at TIU (annual graduation - in-person: 35 people, online: 140-150 people). In the 2024-2025 academic year, career guidance events were held in 19 schools in the region, reaching about 1200 students in grades 8-11. This work is complemented by technical excursions for schoolchildren to the production base (up to 10 excursions annually), organization of preparatory courses for the Unified State Exam (up to 200 listeners), and support for applicant enrollment in universities.

An important link in this chain is interaction with secondary vocational education (SVE) institutions. JSC "Mostostroy-11" is a key employer of the Interregional Sectoral Educational and Methodological Center for SVE in the transport sector and a core employer of the "Transport and Road Construction" cluster within the "Professionalitet" Federal Project in the Tyumen Region, the core of which is the GA POU TO "Tyumen College of Production and Social Technologies". The company's contribution includes not only updating the material and technical base (supply of a truck crane, sets of components) but also adapting curricula, internships for teachers, student internships, including as part of Russian Student Teams (RSO), and concluding targeted training agreements (11 agreements in 2024). In 2025, the employment of 41 SVE graduates is planned.

The next stage is the Bachelor's degree in "Construction". At this stage, students involved in the orbit of the base department begin to immerse themselves in the corporate environment. The final link in this trajectory is the Master's degree in highly specialized and highly demanded programs, such as "Digital Construction" and "Management of Bridge and Overpass Construction Projects on Highways". Thus, by the time of graduation, the university releases not just a person with a diploma,

but a comprehensively trained engineer who has undergone years of targeted training and is well-acquainted with the philosophy, values, and specifics of their future employer's work.

Starting next year, a new educational trajectory will open at the base department - a Specialist degree in the bridge direction: "Construction (Reconstruction), Operation, and Technical Cover of Bridges and Tunnels" with five years of full-time study. In developing the curriculum and syllabi for disciplines, the main emphasis was placed precisely on engineering disciplines, and the content of the syllabi corresponds to modern requirements and the needs of practice.

3.2. The core of training: practice as the main educational module. The fundamental difference of the base department model is the flipped learning paradigm. While in the traditional format, theory is supplemented by episodic practice (which, unfortunately, is quite rare), here the entire educational process is built around the real tasks and cases of JSC "Mostostroy-11". Lectures and seminars are saturated with examples from ongoing projects, analysis of real design documentation, and work with current estimates and technological charts. Students deal not with outdated textbooks but with live materials that are used here and now. It should also be added that the department staff (both faculty and invited specialists from JSC "Mostostroy-11") have jointly written and published more than ten new textbooks and monographs to ensure the quality of the educational process [8].

But the true "gold asset" of the program is the unique internship system called "Vertushka" (Rotation). Its essence is the sequential passage of students through all key departments and production units of the company: Production and Technical Department, Project Management Department, Executive Documentation Department, Pricing Department, Planning and Economic Department, Artificial Structures Design Department, construction and installation sites, and production workshops.

This approach solves several critical tasks. First, it erases the student's stereotypical view of a construction company as a monolith. They see from their own experience how different services interact, how a project is born, how its cost is determined, how structures are manufactured, and how all this is brought together at the site. They begin to understand not only their future function but the entire product creation cycle. Secondly, the "Vertushka" is a powerful tool for career guidance both for the students themselves and for the company. The young person can determine in practice what they are more inclined towards: meticulous calculation work, managing people on a construction site, or technological processes in production. For HR specialists and managers, this is an invaluable opportunity to assess the potential, soft skills and professional inclinations of each intern, in order to subsequently offer them a position where they can fully realize themselves.

3.3. The power of knowledge: practitioner lecturers, relevant courses and digital technologies. The composition of the teaching staff is equally important. At the base department, lectures and practical classes are conducted not only by academic scholars but also by current managers and leading specialists of JSC "Mostostroy-11" and LLC "MStroy": chief project engineers, heads of production departments, leading technologists, and economists. They bring to the classroom not only up-to-date knowledge but also that very context, market understanding, logic of managerial decision-making, and experience in solving non-standard tasks that cannot be found in textbooks. This ensures an unprecedented transfer of knowledge "first-hand".

Simultaneously, leading scientists from the Russian bridge industry are involved in the educational process, guaranteeing the fundamental nature of the training and connection with cutting-edge science. The synthesis of practical business experience and academic depth creates a unique educational environment.

The content of the curricula has also been radically revised. Together with the university, the company developed and implemented a number of unique proprietary courses directly responding to the demands of the modern construction industry. Among them are "Project Management", where students master not only classical project management but also agile methodologies; "Digital Construction", dedicated to working with Building Information Modeling (BIM) technologies; "Pricing and Estimate Preparation", providing an understanding of project economics; and "Lean Manufacturing", aimed at optimizing all processes.

A distinctive feature is the use of modern software in training, including the company's own development, the "MStroy" software package. This is a comprehensive digital construction management system created by leading experts based on the management technologies of JSC "Mostostroy-11". The platform is integrated with the ISUP of the Russian Ministry of Construction and includes modules: "Manager's Office" (dashboards, photo/video reports), "Construction" (work production schedules), "Labor Resource Management", "Machine and Mechanism Management", "Material Management", "Construction Control", "Executive Documentation", "Cost Management" (KS-2, KS-3 forms), and "BI Analytics". The platform is used by over 4500 users from more than 250 organizations, managing over 500 active projects with a total value exceeding 200 billion rubles. Using MStroy in the educational process allows for the training of specialists who are already proficient with corporate tools and ready for effective work in the context of active industry digitalization at the forefront of modern technologies: digital technologies and neural networks.

4. Conclusions: measurable success and a replicable model for Russia's future. The effectiveness of any model is proven by results, and here the base department's indicators speak for themselves. The success is most evident in employment figures. Out of more than 100 department graduates who completed the full cycle of training and the "Vertushka" internship, 60 people were employed by JSC "Mostostroy-11" and its structural divisions. Importantly, this is not just employment but effective adaptation. Moreover, 33 graduates from among those hired or already working in the organization received career promotions in a short time, indicating their high level of training and quick integration. Many undergraduate students combine their studies with part-time work at the company, allowing them to accumulate practical experience while still at the university. Furthermore, a number of department graduates have enrolled in postgraduate studies and, while engaged in research, also teach students, thus preparing the future faculty corps.

The main business result for the company is a radical reduction in the costs of adapting a new employee. A graduate of the base department does not come to the workplace as a "blank slate". They are already familiar with the corporate culture, internal regulations, software, key processes, and, no less important, with the team. Their period of "re-learning" and onboarding is reduced from the traditional 6-12 months to one or two. This is a direct saving of mentors' time, monetary resources for training, and minimization of the risk of errors due to inexperience.

The university also benefits. Constant exchange with production allows the faculty to update their knowledge, stay abreast of the latest technological trends, and obtain material for scientific research from the real sector of the economy. This improves the overall level of teaching across all relevant departments of the university. Furthermore, JSC "Mostostroy-11" provides material support to the base department, equipping it with necessary computer technology, instruments and equipment, and organizing trips for students and faculty to conferences and seminars of various levels.

The experience of the JSC "Mostostroy-11" base department at TIU is more than a successful local project. It is a proven, practice-tested model of public-private partnership in education that demonstrates high efficiency in solving personnel issues. It allows for the training of not just graduates, but motivated, highly qualified practitioner-specialists proficient in both fundamental engineering knowledge and the most modern digital and managerial competencies.

The universality of the principles embedded in this model: continuity of the trajectory (from schools and SVE to university), practice-oriented approach, direct employer participation in the educational process, and the use of real cases and technologies, makes it an effective template for replication in other sectors of the economy: oil and gas, mechanical engineering, energy, and the IT sector. For Russia, whose economic development and technological sovereignty directly depend on the quality of human capital, scaling such experience is not just an option but a strategic necessity. Investments in integrating business and education are investments in the future, in building a solid "bridge" to the next generation of Russian engineers capable of bringing the country's most ambitious infrastructure projects to life.

Acknowledgment. The authors thank the management of JSC "Mostostroy-11" for their assistance in implementing the presented project.

Author declaration: The authors declare no conflict of interest.

Author contribution statement: The authors contributed equally to the preparation of materials and the formation of the structure and text of the manuscript. The authors have reviewed and approved the final version of the manuscript.

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Received: 09/09/2025 Accepted: 29/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-85-92>

INCREASING THE RELIABILITY OF GAS SUPPLY IN UKRAINE

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Abstract. The use of alternative energy sources is one of the most important areas of modern energy policy, aimed both at improving the environment and saving traditional fuel and energy resources. The meaning of the ecological and energy optimization process is not to replace one energy source with another, but economic and industrial transformation, decarbonization and decentralization. Russian aggression has caused unprecedented destruction of the fuel and energy infrastructure of Ukraine, which has created a threat to the reliability of providing end consumers with natural gas. The article examines the processes of formation and development of the country's biomethane industry market as a response to modern global environmental and energy challenges and threats. The possibility of complete or partial replacement from a technical point of view of the traditional and most common organic fuel - natural gas - with biomethane, obtained during the disposal of waste from the agro-industrial complex, household waste, etc. to meet the needs of the housing and communal economy of Ukraine, is justified.

Keywords: natural gas, organic waste, anaerobic technology, biogas plant, biogas, biomethane, physical and chemical properties, gas supply system, reliability of gas supply

1. Formulation of the goals of the article. The use of alternative sources of energy and fuels is one of the most important areas of energy policy in the world, which is aimed at solving current problems: improving the state of the environment and reducing the consumption of traditional organic fuels [1, 2]. These issues are particularly important in Ukraine in today's conditions - the long-term military aggression of the Russian Federation, which has led to the significant destruction of the fuel and energy infrastructure of our country (in 2025 - at least a third of its own natural gas production [3]). **The purpose of this article** is to study the possibilities of partial or even complete replacement of natural gas with biomethane to regulate hourly irregularity of gas consumption or to provide end consumers with fuel, for example, in the housing and communal economy. **Statement of the problem.** After gaining independence, Ukraine inherited a huge, "voracious" industry from the point of view of energy consumption. For example, in 1991, the country used an incredible 114 billion m³ of blue fuel for its own needs, mostly of imported origin.

Over time, Ukraine has lost or modernized a significant part of its industrial facilities, and consumption has significantly decreased. Own production has practically not changed - within 20 billion m³. Today, the state no longer needs as much gas as it did in 1991. During martial law, detailed statistics on gas consumption are classified, but according to the results of 2023, Ukraine used only 19.8 billion cubic meters of gas.

Gross production of natural gas in Ukraine in 2024 amounted to 19.12 billion m³. Compared to last year, it increased by 2.2%. The main part of the fuel is consumed by the population, as well as heat producers in populated areas (communal energy enterprises) - about 11 billion m³. The share of industry in 2025 will be about 4 billion m³, and the rest (about 5 billion m³) will go to electricity production.

According to the provisions of the Energy Strategy [4], natural gas will continue to be the main

energy carrier/fuel in Ukraine. Its share is almost a third of all primary energy consumption. At the same time, it is the most ecological fuel compared to other traditional ones, including and alternative [5].

Available natural gas resources (almost all the needs of the economy were met at their expense earlier) and developed gas transportation and gas distribution networks of settlements, one of the largest underground storage systems for seasonal gas storage in Europe, contribute to the priority use of blue fuel in the state. However, the destruction of infrastructural objects of gas production, transportation and distribution systems, which is ongoing and reached its peak in the second half of 2025, imposes significant restrictions on ensuring the reliability of energy supply to end consumers [3]. Thus, there is currently a problem of maintaining the gas infrastructure in working condition and providing consumers with blue fuel. One of the ways to solve the existing problem is to replace natural gas in the future (in full or in part) with biogas of artificial origin, at least in the warm period of the year.

2. Analysis of research and publications. On an industrial scale, biogas can be obtained from several sources: waste from agricultural production (plant and animal husbandry), solid household waste landfills. Biomass is an organic substance with a certain chemical energy that can be converted into electrical energy or fuel. The source of primary biomass is terrestrial and aquatic vegetation, and the source of secondary biomass is waste, which is formed after the collection and processing of primary biomass into marketable products and is caused by the life activities of people and animals (wood, straw, vegetable waste from agriculture, animal husbandry and poultry waste, organic part of household and industrial waste). The intensification of agricultural production and the expansion of agricultural lands have led to an increase in the amount of waste and its impact on the natural environment. According to the data of statistical observations [6], of the more than 13.5 million tons of agricultural waste generated annually, the most massive are:

- 1) plant waste (7.74 million tons);
- 2) animal excrement, urea and manure (4.94 million tons);
- 3) waste of animal origin and mixed food waste (0.9 million tons).

However, statistical data do not fully reflect the real state of affairs. Thus, with a gross collection of grain at the level of 50 million tons, up to 25 million tons of straw can be formed. In the case of an increase in the gross collection to 80 million tons, the amount of straw also increases proportionally to 40 million tons. Another source of agricultural waste is animal husbandry and poultry farming, where the main type of agricultural waste is manure. There are about 13 million head of livestock in Ukraine. If, on average, one animal produces 10 kilograms of manure per day, up to 50 million tons of manure can be produced in a year. A population of 1.5 million chickens produces more than 100 tons per day. In total, about 500,000 tons of bird droppings are produced in Ukraine every year. There are also other waste products in poultry farming. According to regulations, the amount of waste can be 3.5% of the total amount per year, which amounts to 3,570 tons of biowaste based on the average weight of a bird of 500 grams.

In general, the amount of possible energy potential due to the use of renewable biomass resources in Ukraine is about 20 million t o.e./year, of which the technically available energy potential is estimated at 12 million t o.e./year; this is approximately 7% of the total consumption of primary energy resources in Ukraine. The most effective and promising basic method of utilization of livestock waste is methane "fermentation" or bimechanogenesis - a long-known process of converting biomass into energy. In the process of processing the raw material (liquid manure with a moisture content of 90-91%) by the method of methane fermentation, three primary products are formed, namely: dehydrated sludge, biogas and liquid effluents (fugate after the centrifuge). Methane "fermentation" technology allows obtaining, in addition to biogas, high-quality fertilizers and protein-vitamin feed additives (vitamin B-12, cryptogumin, etc.), and in fact, is waste-free. Therefore, in developed industrial countries, the need to build biogas plants is often determined precisely by solving environmental problems. Biogas is a combustible gas with a content of 60-80% methane, 40-20% carbon dioxide, up to 0.1% hydrogen sulfide and a small amount of nitrogen, oxygen, and hydrogen. The gas burns with a blue flame, there is no smell. The heat of combustion is within 21-23 MJ/m³. The

amount of biogas that can be obtained from 1 m³ of raw material varies between 15-17 m³/day.

The main technology, the result of which is the production of biogas, is anaerobic biotechnology, that is, fermentation of organic substances in conditions of complete absence of oxygen. Anaerobic fermentation, the development of bacteria is largely determined by the ratio of carbon C and nitrogen N. The most favorable conditions are created when the ratio C/N = 10-16. At lower values, such an amount of ammonia is formed in the fermentation process that it becomes toxic to bacteria. In the opposite case, a small amount of nitrogen limits the process of methane fermentation. For an optimal ratio, different types of waste are mixed in a bioreactor, obtaining a higher gas yield (up to 10%). Temperature is one of the most important parameters that determines the speed of the fermentation process and the productivity of the biogas plant. So, for example, an increase in temperature reduces the methane content in the total volume of biogas. At the same time, energy consumption increases. Anaerobic waste disposal technology has many advantages over aerobic:

1. 0.35 m³ of pure methane or 0.45 m³ of biogas is released for 1 kg of raw material processed with this technology under normal conditions and with a consumption of 5 kg of dry biomass per 1 m³ of water. On the scale of Ukraine, this can amount to almost 1 billion m³ of biogas annually - a full-fledged energy carrier that can replace natural gas in all cases of its use. Combustion of 1 m³ of biogas in a modern cogeneration unit gives the opportunity to obtain 2 kWh. of electricity and 4 kWh thermal energy in the form of hot water.

2. When using anaerobic fermentation, only 0.03 kg of biomass is produced in the form of waste per 1 kg of raw material. The remaining organic substances are processed into methane (that is, into biogas).

For the climatic conditions of Ukraine, in the cold period of the year, the fermentation medium should be heated, possibly using a part of the outgoing biogas, to a temperature of approximately 35 °C. Some bacteria "work" at 55 °C. They are used if it is necessary to decompose the material as quickly as possible, and not to obtain an additional amount of biogas. Increasingly, solar power plants are used as energy sources for biogas plants. Biochemical processes during fermentation take place in three stages, and each stage is provided by its own group of anaerobic bacteria.

1. Insoluble, biodegradable materials (for example, cellulose, polysaccharides, fats) are broken down into carbohydrates and fatty acids. In a working biogas generator, this happens at a temperature of 25 °C per day.

2. Acid-producing bacteria form mainly acetic and propionic acids. This stage at the same temperature also lasts a day.

3. Bacteria, forming methane, slowly, within 14 days, at a temperature of 25 °C, completely ferment the initial products, producing 70% CH₄ and 30% CO₂ with small impurities of H₂ and possibly H₂S.

Methanogenic bacteria are sensitive to the value of the pH indicator: the conditions in the environment should be moderately acidic (pH = 6.6-7.0) and, of course, not lower than 6.2. A certain content of nitrogen and phosphorus is required: about 10 and 2% of the mass of dry material, respectively. The golden rule of ensuring a successful process is to maintain constant conditions in terms of temperature and supply of starting materials. Under stable conditions, appropriate populations of bacteria suitable for these conditions can be bred. Biogas generation becomes economically justifiable when a suitable biogas generator works on the processing of an existing waste stream. Examples of such flows can be effluents from sewage systems, pig and dairy farms, meat processing enterprises, etc. Economy in this case is connected with the fact that there is no need for preliminary waste collection, organization and management of the process of their submission. It is known in advance how much and when the waste will arrive, and all that remains is to process it into biogas and fertilizers. Obtaining biogas is especially effective for agro-industrial complexes, where it is advisable to achieve the implementation of a full ecological cycle in installations of different productivity. In such complexes, manure is subjected to anaerobic fermentation followed by aerobic treatment in open pools. Biogas is used, as a rule, in cogeneration plants for the combined production of electricity and thermal energy. Algae are grown in the pools, which are fed to livestock. After aerobic fermentation, fully treated waste can be fed into artificial and natural ponds for breeding fish and waterfowl before being used as fertilizers. The success of the implementation of such schemes directly depends on the

quality of the system development of the entire project, the degree of standardization of structures, and the regularity of maintenance.

The potential of biogas production in Ukraine is about 10 billion m³/year, which will reduce carbon dioxide emissions by approximately 20 million tons/year [7] and, accordingly, reduce "thermal" environmental pollution. A biomethane plant that can produce about 10 million m³ of biomethane per year costs about EUR15 million. If you buy raw materials for EUR40/t (bales of straw or corn stalks), which will provide additional income for farmers, and sell biomethane for EUR900/1000 m³, then the profitability of such projects becomes interesting for investors - at the level of 25% profitability [7]. In Ukraine, there are more than 400 cities, 800 urban-type settlements and 25,000 villages under the control of the territorial authorities, whose local self-government bodies are fully responsible for the organization of solid waste management services. The volume of solid household waste generation in Ukraine has recently been approximately 50 million m³ every year or about 11 million tons (excluding temporarily occupied territories). Despite the fact that the population of Ukraine is constantly decreasing, the volume of household waste generation, on the contrary, is increasing.

The waste problem in Ukraine, compared to European countries, is particularly large and significant due to the dominance of resource-intensive multi-waste technologies in the national economy, as well as the lack of an adequate response to its challenges for a long time. The significant scale of resource use and the energy and raw material specialization of the national economy, together with the outdated technological base, determined and will continue to determine high rates of waste generation and accumulation. Currently, the average amount of household waste in Ukraine is 250-300 kg/year per person. The dominant method of handling household waste remains its removal and burial in landfills and landfills. Only 5.8% of generated household waste is processed, including 2.71% (1.3 million m³) is disposed of (usually incinerated), 3.09% (1.53 million m³) is sent to waste processing complexes, and about 0.003% (2000 m³) is composted. The rest, about 94%, are placed in landfills and landfills, of which there are almost 5.5 thousand in Ukraine, of which more than a third are either overloaded or do not meet the environmental safety standards in force in Ukraine. According to expert assessments, more than 99% of operating landfills do not meet European requirements. For example, Directive 1999/31/EC [8] provides for the following measures for the disposal of combustible gases:

- 1) control of accumulation and migration of landfill gas;
- 2) landfill gas must be collected at all landfills that accept biodegradable waste, as well as processed and used; if the collected gas cannot be used to generate energy, it must be burned;
- 3) collection, processing and use of landfill gas must be carried out in a way that minimizes damage to the environment or its deterioration, as well as the risk to human health.

Excessive dependence on household waste disposal can no longer be the basis of household waste management in Ukraine. In addition, signed in 2014 The Association Agreement between Ukraine, on the one hand, and the European Union, the European Atomic Energy Community and their member states, on the other [9] requires Ukraine to take immediate and decisive steps to implement European standards in the relevant field. If we compare the physico-chemical properties of biogas with the requirements for the quality of natural gases established, for example, by the Code of the Gas Transportation System [10], then without additional purification, biogas is unsuitable both for transportation through existing networks and for use by traditional gas equipment. Various methods of using such biogas are known in world practice, starting from elementary flaring directly at the place of generation without utilization of the heat of combustion products to significant purification with bringing the methane content to 90-95% (the so-called biomethane) or the production of marketable carbon dioxide [11]. Currently, in Ukraine, in the conditions of the partial destruction of the gas infrastructure, the use of biogas refined to the level of biomethane will avoid the emergency shutdown of the gas transportation and gas distribution systems, and will provide end consumers with blue fuel.

Each ton of household waste in the process of anaerobic processing of organic mass releases up to 200 m³ of biogas. In total, the state can produce up to 1 billion cubic meters of biomethane per year. And if there are practically no problems with the utilization of biomethane [11], then a significant additional amount of carbon dioxide, which is the main component of greenhouse gases - causes an

increase in "thermal" pollution of the environment. Thus, by combining the processes of electricity generation from alternative sources, wind (WES) and solar (SES) with enterprises for the production of biomethane with separate release of carbon dioxide and subsequent methanation of the obtained CO₂ with the help of "green" H₂, the following problems can be solved:

1) significantly reduce environmental pollution by agricultural production waste, solid household waste, etc. through their disposal, followed by beneficial use of the freed areas of landfills, landfills, etc.;

2) to regulate the unevenness of electricity consumption by reducing the share of thermal generation as the main method in Ukraine and, accordingly, reducing emissions of pollutants and greenhouse gases into the atmospheric air when burning coal the main fuel for thermal power plants;

3) cancel the withdrawal into reserve of nuclear power plant units that generate the cheapest electricity;

4) significantly reduce the consumption of traditional organic fuels, for example, natural gas, as well as abandon their purchase abroad.

Fig. 1 shows a schematic diagram of methane synthesis using electricity from alternative sources and carbon dioxide, which is produced during the production of biomethane.

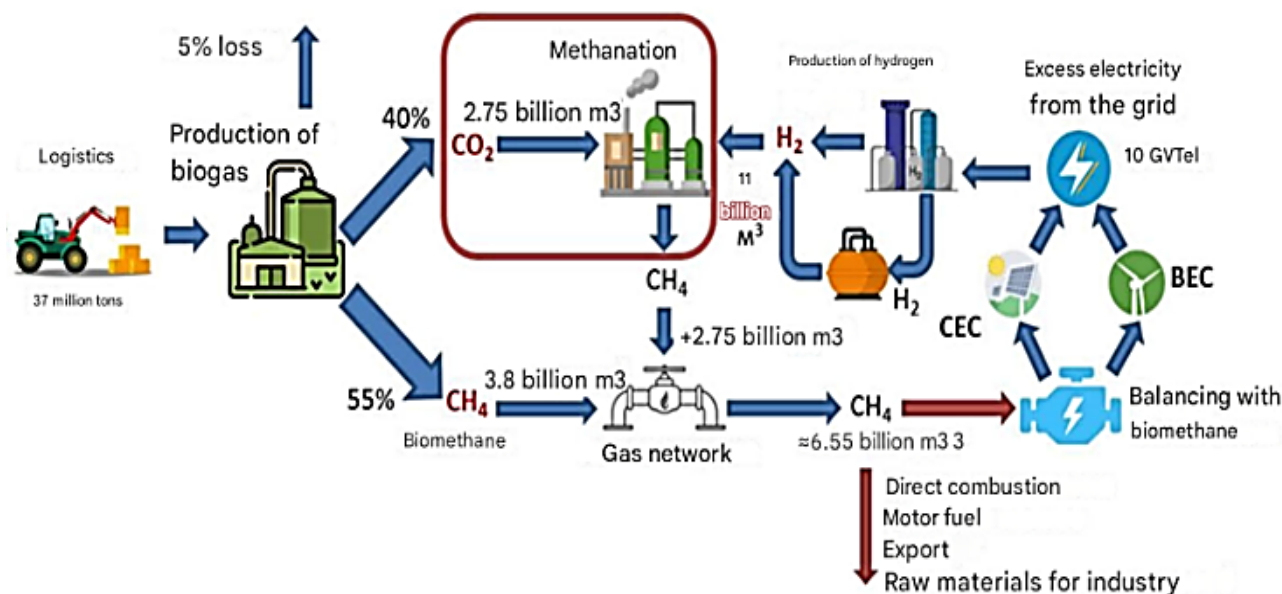


Fig. 1. Schematic diagram of carbon dioxide methanation [12]

The use of such a scheme will allow, in addition to the potential 10-11 billion m³ of biomethane in Ukraine, to annually add up to 7 billion m³ of synthetic CH₄, which can be obtained from CO₂ of biomethane plants and green H₂ with the help of electricity from alternative sources. In addition, another component of biomethane production is the fermented fraction, which contains nitrogen, phosphorus and potassium, as well as other microelements, which helps to increase soil fertility.

3.Results and discussion. The formation of the biomethane industry in Ukraine began in 2021, when the price of natural gas in Europe reached 2100 EUR/1000 m³, and the cost of biomethane production was (depending on the type of raw material) from 600 to 900 EUR/1000 m³ [13]. And therefore, at the first stages of its development, the most likely scenario is the export of the vast majority of produced biomethane to EU countries (the price of such fuel is from 1,200 to 1,500 EUR/1,000 m³). In Ukraine, currently (from an economic point of view) production is unprofitable for use on the domestic market. On the Ukrainian Energy Exchange, the weighted average price of natural gas per month for November 2025 is UAH 20,551.67 or EUR 419.64 per 1000 m³ [14].

In Ukraine, 7 biomethane plants should be operational by 2025, and investors have started construction of at least 10 more, each of which can produce 5 million m³ of gas per year. Currently,

there are about 80 biogas capacities in the state, 20 of which can be cost-effectively upgraded to biomethane (with purification from impurities: carbon dioxide, hydrogen sulfide, nitrogen, etc.) [13]. Physico-chemical properties of such gas, obtained at one of the enterprises in Khmelnytskyi region, according to the quality protocol from LLC "Operator GTS of Ukraine" according to the results of chromatographic analysis, as well as calculated in accordance with the requirements of regulatory and technical documents in force in Ukraine, are listed in Table 1.

Table 1. Biogas quality indicators [15, 16]

Indicator	Meaning
1. The content of the component, %:	
- methane	98,1251
- oxygen	0,0340
- nitrogen	1,0595
- carbon dioxide	0,6814
2. Density (20/25 °C; 0.101 MPa), kg/m ³	0,6821
3. Heat of combustion, MJ/m ³ :	
- higher	36,3990
- lower	32,8013
4. Wobbe number, MJ/m ³ :	
- higher	43,5865
- lower	48,3671
5. Content of impurities, g/m ³ :	
- hydrogen sulfide	< 0,006
- mercaptan sulfur	< 0,02
- mechanical	<0,0005

After obtaining biomethane, the question arises of determining the ways of its possible use, for example, to increase the reliability of existing gas supply systems in populated areas. The volumes of fuel generation and the regularity of its deliveries impose conditions on the methods of its transportation to consumers.

First of all, biomethane can reach settlements in rural areas, a large part of which is connected to existing high-pressure gas distribution networks (0.6-1.2 MPa) - the so-called interurban gas pipelines of network gas [17, 18]. The priority and main consumer is the population that uses gas to meet economic and household needs and heat supply needs. Large-scale industry is usually absent. Accordingly, in rural areas gasified by network natural gas, the seasonal irregularity of blue fuel consumption is characteristic: in the warm period of the year, there is no need for heat supply of buildings and structures of various purposes. Thus, in this period, gas consumption is up to 15% of the total gas consumption in the heating period. Determination of the diameters of gas distribution network pipes, calculation and selection of equipment for gas regulation units, gas metering units, etc. are performed for maximum hourly costs [17]. Accordingly, in the warm period of the year, the storage capacity of the gas distribution network can be used for fuel storage. If there are large agro-industrial holdings nearby, they can become enterprises for the generation of biogas with subsequent conversion into biomethane. In this case, it is advisable to connect the biomethane plant to the existing gas distribution network, followed by a check of the throughput capacity, if necessary, its reconstruction should be performed. In the warm period of the year, with appropriate calculations, network natural gas can be completely replaced by biomethane.

If there is no network of inter-village gas pipelines near the biomethane plant, then the best option is its transportation in a liquid state (the property of any gaseous medium is used to change its aggregate state when the temperature decreases and the pressure increases - to turn into a liquid), which makes further storage of biomethane convenient (the volume decreases in 600). Thus, an

infrastructure similar to the one for transportation, storage and use of liquefied hydrocarbon (propane-butane) gases can be created. The main difference is only in the parameters of energy carriers. In European countries, liquefied gases are the most popular compared to other types of fuels.

Such autonomous gas supply installations consist of the following structural elements: a container for storing biomethane in liquefied form (cryogenic tanks with a volume of 1 to 60 m³, depending on the mode of gas consumption), atmospheric type evaporators for regasification (in the cold season of the year - by heating), control and measuring devices, control and regulation systems.

For an individual cottage built near Kyiv for a family of 4, in which a domestic gas stove is installed to meet the household needs of the residents, a water boiler for heating and hot water supply, in the cold period of the year the total maximum hourly gas consumption will be 11, and in the warm period - 1.5 m³/h. Thus, in the warm period of the year, gas consumption is reduced by 86%. For a cottage town built with 50 similar houses, this is, respectively, 438 and 27.5 m³/h, or a reduction in consumption by 93% (taking into account the coefficients of unevenness of simultaneous operation of gas appliances and water boilers) [17].

The average volume of fuel consumption by the gas equipment of the cottage during the month in the heating/non-heating period will be, respectively, 3410/174 m³/month. In the warm season, a gas storage unit with a volume of 3 m³ with an evaporator capacity of at least 1.5 m³/h is suitable for providing an individual house. For an uninterrupted supply of gas to the consumer during the non-heating period (6 months of active consumption), it is necessary to fill the tank of the indicated volume at least once every 6 months, during the heating period - at least 2 times a month, simultaneously increasing the performance of the evaporator by installing a heater.

For a residential group in an urban-type village consisting of five 5-story buildings with 65 apartments each, the kitchens of which are equipped with instantaneous water heaters and domestic stoves, for autonomous gas supply it is necessary to connect a tank with a capacity of 60 m³ with an evaporator capacity of at least the total maximum hourly gas consumption - 170 m³/h. during round-the-clock work. Heating needs in the cold period of the year are provided from alternative sources, for example, ground source heat pump installations. During the year, the tank should be filled at least 9 times. The distance from such a gas reservoir installation when placed underground to the nearest house should be at least 40 m [17]. For backup gas supply in the event of emergency situations near the main gas regulation points, small gas distribution stations that provide fuel to settlements with a population of up to 5,000 people, it is necessary to install mobile installations with tanks with a volume of 40-60 m³, equipped with evaporators with a capacity (during round-the-clock operation) of 200 m³/hour or more.

4.Conclusions. Currently, Ukraine, despite the full-scale aggression of the Russian Federation, is implementing its strategic course - the acquisition of full membership in the European Union, which, among other things, involves the decarbonization of the economy (increasing energy efficiency, disposal of accumulated waste, development of renewable energy sources and circular economy, and synchronization with the "European Green Course" initiative). Having declared its commitment to the principles of sustainable development, Ukraine recognized that the development of renewable energy sources, reducing the consumption of traditional organic fuels, etc., are important factors in increasing the level of energy security and reducing the anthropogenic impact of the economy on the natural environment. Replacing natural gas with biomethane, obtained as a result of disposal of household waste and agricultural waste, will contribute to increasing the reliability of gas supply to end users, use of the existing potential of the gas infrastructure, continuation of its trouble-free operation, etc.

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Received: 05/09/2025 Accepted: 16/11/2025 Published: 30/12/2025

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<https://doi.org/10.58225/sw.2025.2-93-108>

RESILIENT FUTURES: REASSESSING TRADITIONAL HOUSING MODELS FOR LONG-TERM SUSTAINABILITY

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Abstract. Sustainability has emerged as a central challenge in contemporary architecture and urban planning, driven by climate change, rapid urbanization, and the depletion of natural resources. However, many of the solutions sought today were already embedded in the construction logic of traditional dwellings, particularly in rural and vernacular contexts. Traditional architecture embodies the key principles of sustainability - the use of local and renewable materials, climate-adaptive spatial planning, passive ventilation, and thermal regulation - long before these concepts were formally theorized. This study re-evaluates traditional Azerbaijani architecture through the lens of sustainability, analyzing dwellings and monumental structures across various regions of the country. Comparative references are drawn from vernacular architectures in Iran to contextualize regional similarities in climate-responsive design. The analysis focuses on material typology, wall thickness, structural systems, and passive environmental strategies, framed within broader socio-cultural and ecological dimensions. The paper argues that traditional architecture should be recognized not merely as cultural heritage but as a resilient and contextually adaptive model for contemporary sustainable design. Finally, the study proposes an integrative framework for embedding vernacular knowledge into modern architectural education, conservation policy, and sustainable building practices.

Keywords: vernacular architecture, climate-adaptive design, local building materials, passive thermal performance, architectural heritage, sustainable rural development

1.Introduction. In the twenty-first century, sustainability has become one of the most pressing challenges facing architecture and urban planning. Accelerating climate change, rapid urbanization, the depletion of natural resources, and rising energy demands have created a need for new architectural and design strategies. Today, the construction sector faces significant pressure in terms of its ecological footprint, carbon emissions, and energy consumption. Within this context, sustainable architecture can no longer rely solely on technological innovation; it must also draw upon the historical knowledge and traditional construction cultures that once ensured environmental harmony and resilience.

Many of the principles that modern architects now rediscover under the banner of “sustainability” — the use of local materials, climate-responsive design, passive energy strategies, and social adaptability — were already embedded in traditional building practices across diverse regions centuries ago. Vernacular dwellings, particularly those in rural contexts, were designed in harmony with their environment: minimizing energy use, recycling materials, and reflecting social and cultural patterns of life [1]. Traditional Azerbaijani architecture, much like that of Anatolia and the South Caucasus, exemplifies how adaptation to nature and respect for the environment shaped the very foundation of architectural form.

Similar architectural patterns can be observed beyond Azerbaijan’s borders, particularly in Tabriz, Iran — a city sharing both the climatic conditions and the cultural continuum of the region. The

caravanserais, the mosques and the semi-subterranean adobe dwellings of Tabriz demonstrate how architectural aesthetics and environmental functionality coexisted. Thick masonry walls, low ceilings, and narrow window openings contributed to thermal stability by retaining warmth in winter and maintaining coolness in summer. Moreover, the compact urban fabric, where residential and public buildings were physically interconnected, helped reduce heat loss and energy demands. These features embody what is now recognized as the early practice of “passive design.”

Scholarly literature emphasizes that sustainable architecture extends beyond energy efficiency; it also encompasses social, cultural, and economic adaptability [2]. Traditional buildings, in this sense, form the nucleus of sustainability — they minimize environmental impact, optimize material and energy resources, and reflect community-based patterns of living. The architectural heritage of Tabriz and Absheron therefore represents a significant case for both theoretical and practical investigation.

The objective of this study is to comparatively analyze traditional residential structures in the Absheron and mountainous regions of Azerbaijan alongside those in the city of Tabriz, Iran, through the lens of sustainability. The research aims to identify how these traditional architectural models address contemporary ecological challenges and to determine which of their design principles can be effectively transferred to modern architectural practice. The analysis focuses on spatial organization, material selection, structural systems, stylistic features, and climate adaptability. The central hypothesis is that these traditional architectural forms are not merely historical artifacts but offer practical frameworks for future sustainable design — embodying principles that remain both relevant and applicable in the era of global environmental change.

Table 1. Transfer from Vernacular to Sustainable Architecture

Traditional principle	Modern equivalent	Sustainability benefit
Use of local natural materials (clay, brick, stone)	Biodegradable, low-carbon materials	Reduction of carbon footprint
Courtyard-based spatial layout	Passive cooling strategies	Decreased energy consumption
Thick walls and small windows	Thermal mass strategy	Improved temperature stability
Harmony with natural site	Bioclimatic design	Climate-responsive structure
Social-spatial cohesion	Community-based planning	Enhanced social sustainability

2. Research methodology and approach. This study employs a comparative and analytical methodological framework to examine the sustainability features of traditional dwellings located in the Baku, Absheron and mountainous regions of Azerbaijan, as well as in the city of Tabriz, Iran. The principal aim is to identify how vernacular architecture aligns with modern principles of sustainable design in terms of climate adaptability, material selection and energy efficiency.

The research process consisted of three main stages:

1. a systematic review of scientific literature on vernacular sustainability;
2. a typological and structural analysis of selected case studies;
3. a comparative interpretation of results against contemporary sustainable architectural frameworks.

The case studies were selected using a purposive sampling approach, focusing on representative examples of courtyard houses, thick masonry walls and locally sourced construction materials such as stone, brick, clay and timber. Azerbaijani examples were drawn primarily from Absheron villages and mountain settlements in the other regions, while Iranian examples were taken from the historical neighborhoods of Tabriz.

This regional pairing ensured climatic comparability, as both study areas exhibit a semi-arid continental climate characterized by hot summers and cold winters [3, p. 109]. The sustainability potential of traditional architecture was assessed through four key parameters:

1. Microclimate and courtyard design-The courtyard height-to-width (H/W) ratio, spatial form (rectangular, U-, or L-shaped), orientation, and vegetation cover were examined. Previous studies

indicate that courtyard geometry and orientation can reduce indoor air temperatures by 0.5–5 °C in hot and arid regions [4, p. 146; 5, p. 92].

2. Building materials and structural systems-Wall thickness, material composition (stone, adobe, brick), roof type (flat or gabled) and window geometry were evaluated. The use of local natural materials significantly reduces carbon footprint while ensuring thermal stability and ecological compatibility [6, p. 74; 7, p. 118].

3. Passive ventilation and thermal regulation-The configuration of semi-open spaces (sofa, veranda), air circulation paths, and the interaction between thermal mass and natural ventilation were analyzed. Studies demonstrate that ventilated courtyards and semi-enclosed layouts generate passive cooling effects driven by pressure and temperature differentials [8, p. 225; 9, p. 243].

4. Socio-spatial adaptation and resource sustainability-Indicators such as community-based spatial organization, local sourcing, and material reuse were included to address the social and cultural dimensions of sustainability [10, p. 53; 2, p. 67].

Three principal data sources informed the study:

-Literature review: Key works examining the environmental performance of courtyard architecture were reviewed, including *Passive Cooling Effects of Courtyards* [3], *Courtyard Design Variants and Microclimate Performance* [4], and *A Ventilated Courtyard as a Passive Cooling Strategy in the Warm Humid Tropics* [8].

-Typological and morphometric analysis: For each selected dwelling, plan depth, courtyard ratio, wall thickness, window dimensions, and orientation were recorded based on architectural surveys, measured drawings and archival documentation [11, p. 24].

-Material and Assembly Profiling: The thermal and moisture-regulating properties of stone, earth and timber were analyzed using the technical parameters outlined by Carole Ryan in *Traditional Construction for a Sustainable Future* [11, p. 112].

The analytical framework comprised three stages:

A. Courtyard performance assessment-The passive cooling potential of courtyard layouts was assessed according to orientation, wall height, vegetation and shading. Recorded parameters were compared against established empirical benchmarks reporting temperature reductions of 0.5–5 °C [3, p. 110; 5, p. 95].

B. Structural and material evaluation-Wall materials, thickness and window proportions were analyzed in relation to “thermal mass strategy.” Ventilation potential was further interpreted based on the spatial relationship between courtyards and transition zones (sofa/veranda) [8, p. 229].

C. Three-pillar sustainability model-Each case was evaluated using a three-pillar framework encompassing environmental, social, and cultural indicators.

- *Environmental*: energy efficiency and material renewability;
- *Social*: adaptability to community and lifestyle patterns;
- *Cultural*: preservation of vernacular knowledge and building craft.

The scoring matrix situates each dwelling along a continuum from “heritage prototype” to “transferable sustainability model” [7, p. 122].

As no environmental measurements were performed, findings rely on comparative inference using temperature and orientation data reported in prior studies. Seasonal heating penalties associated with deep courtyards were acknowledged but not numerically simulated. Nevertheless, results were triangulated across hot-arid and warm-humid climate studies to ensure contextual reliability [4, p. 148].

3.Results and discussion. The renewed interest in the sustainability of medieval and vernacular architecture arises from its holistic adaptation to both natural conditions and human needs. Traditional Azerbaijani and Tabriz dwellings demonstrate how the synthesis of material, climate, and social structure historically produced environmentally attuned architectural systems. These buildings formed from locally available resources such as limestone, baked brick, timber and clay, anticipated many principles of modern ecological design: low embodied energy, thermal inertia and passive climate control [12, p. 176]. In Azerbaijan, vernacular dwellings evolved through diverse typologies—*qaradam*, *pəyə* and *eyvanlı ev*—corresponding to settlement type (permanent or nomadic), terrain, and

resource availability [13]. Mountain dwellings in Ganja and Nakhchivan used thick masonry or semi-subterranean construction for insulation; plains settlements favored lightweight reed or cane walls allowing air permeability.

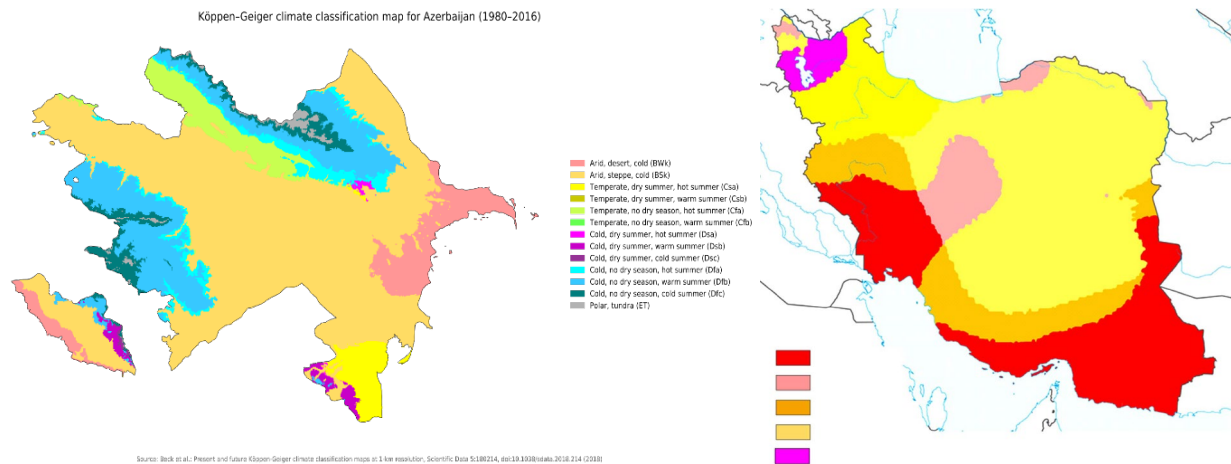


Fig. 1. A.Climate map of Azeerbaijan based on Köppen-Geiger classification method for 1980–2016
b.Climate map of Iran based on Köppen-Geiger classification method,
https://en.wikipedia.org/wiki/Climate_of_Azerbaijan

The *qaradam* houses of the Small Caucasus, composed of clay, stone and timber, balanced thermal mass and humidity buffering, preserving warmth in winter and coolness in summer. In contrast, Absheron architecture shaped by aridity, salt exposure and prevailing northern winds, relied heavily on limestone masonry. The use of lime-clay plaster prevented material expansion under thermal stress, anticipating what contemporary material science terms *adaptive fabric performance*. The Absheron Peninsula, as described by Fətullayev-Fiqarov [14] and Mehtiyev [15], represents a microclimatic laboratory of sustainability. Here, houses were oriented south or southeast to capture limited winter sun while shielding against the *gilavar* wind. Flat earthen roofs with stone gutters enabled rainwater management and provided shaded outdoor sleeping areas—an example of multifunctional envelope design. Kitchen domes (*dubla*) above the *təndir* served simultaneously as ventilation and as thermal chimneys.

Such domed exhausts, according to Akan et al. [16, p. 184], are parallel to Anatolian “*hayat-ocak*” systems, where semi-enclosed courtyards regulate indoor air quality through buoyancy-driven flow. In Tabriz, the material palette shifted toward baked brick and plaster composites, allowing seismic resilience in a tectonically active environment. As highlighted by Cao et al. [7], brick masonry with lime mortar achieves both compressive strength and energy retention, reducing annual heating demand by up to 20%.

Table 2. Comparative material logic in Azerbaijani and Iranian traditional dwellings.

Material	Typical regions	Performance characteristics	Sustainability advantage
Baked brick	Tabriz, Nakhchivan	Seismic stability, thermal retention	Longevity, energy efficiency
Limestone	Absheron, Buzovna	Breathable, adaptive to temperature change	Climate responsiveness
Timber (oak, plane)	Shaki, Qax, Tabriz	Structural–decorative synergy	Renewable, low embodied carbon
Clay/plaster	Ganja, Tabriz	Thermal mass, moisture regulation	Passive insulation, recyclability

Vernacular builders optimized wall thickness (60–80 cm) to stabilize diurnal temperature variation, mirroring the performance thresholds later verified in empirical studies of Anatolian courtyard houses [4].

Table 1 summarizes the comparative material logic of Azerbaijani and Iranian traditional dwellings. Baked brick in Tabriz and Nakhchivan displayed *anti-seismic elasticity* through interlocked joints; limestone on Absheron provided permeability and reflectivity; timber in Shaki–Qax added flexibility and aesthetic continuity; and clay layers acted as renewable insulation. These findings coincide with Örmecioğlu et al. [17] who observed that mixed timber–adobe (*hımış*) systems in Bozova (Turkey) offered high durability with minimal maintenance, emphasizing repairability as a core sustainability trait.

The courtyard-centered plan, common to both Azerbaijani and Anatolian vernacular housing, constitutes a passive climatic device. Courtyards function as thermal buffers: shading in summer, allowing solar gain in winter, and channeling airflow through openings [9]. In Absheron and Shaki, inner yards enclosed by high walls produced microclimates 3–5 °C cooler than external ambient temperature—consistent with empirical observations from Korkuteli houses [16, p. 183]. Orientation towards prevailing winds and the inclusion of semi-covered spaces (*eyvan* or *sofa*) facilitated continuous cross-ventilation, an approach parallel to the bioclimatic zoning of Mediterranean courtyard houses [8].

The hybrid masonry-timber technique found in Azerbaijani shrines such as the *Qarapaltar Piri* (Buzovna, 14th century) and Anatolian *Bozova Houses* shows how compressive and tensile materials were balanced to resist seismic stress. These techniques prefigure today's composite structural strategies aimed at ductility and load distribution. The domed and arched typologies—rooted in Persian-Caucasian masonry logic—ensured the diffusion of vertical loads and enhanced wind resistance. Similar structural wisdom was observed by Akan et al. [16, pp. 185–186], where timber frames integrated with adobe infill extended building life beyond 80 years with minimal repair.

Vernacular sustainability extends beyond physical endurance; it encapsulates cultural continuity and self-maintenance capacity. As noted in the Korkuteli–Bozova study, user participation in construction fosters long-term maintenance literacy among residents [16, p. 187]. In Azerbaijani contexts, families routinely repaired roofs and facades using community labor and locally mixed lime plaster, a practice that sustained both craftsmanship and social cohesion. However, contemporary threats—including unregulated restoration, salt efflorescence and wind erosion on the Absheron Peninsula—undermine this inherited sustainability. Similar degradation patterns are documented for Anatolian earthen structures in *Renewable and Sustainable Energy Reviews* [18], underscoring the need for climate-adaptive conservation protocols.

Traditional Azerbaijani and Tabriz architecture embodies a pre-industrial model of circular economy: local sourcing, low-waste construction and climatic synergy. To re-embed these logics within contemporary practice, several strategic implications arise:

- Design translation: Develop architectural guidelines that reinterpret courtyard and wall-mass systems as modern passive design tools.
- Material substitution: Promote local equivalents of lime, clay and renewable timber over synthetic composites.
- Adaptive restoration: Encourage conservation methods aligned with regional humidity, wind and salt exposure profiles.

Thus, vernacular architecture in the South Caucasus and Northwest Iran offers a tested empirical framework for sustainable building—combining environmental intelligence, structural resilience and cultural identity. Reintegrating this heritage into present design education, urban planning and restoration policy is therefore both a scientific necessity and a cultural imperative.

In contemporary architectural discourse, sustainability has become a strategically significant and globally pressing issue. Under the combined impact of climate change, rising carbon emissions, resource depletion and rapid urbanization, architecture today is assessed not only by its technological innovation or aesthetic quality but also by its ecological responsiveness and social adaptability [7, p. 132,19]. Within this context, vernacular and monumental architectures are increasingly recognized as

early and empirically tested models of sustainable design.

Vernacular architecture represents a harmonious synthesis of material, form and function, shaped by the intelligent use of local climate, topography, social structure and available resources [13, pp. 51–52; 20]. Across Azerbaijan particularly in Nakhchivan, Absheron, Ganja, Shamakhi, and Shaki–Zaqatala and in the culturally and climatically related city of Tabriz, construction materials were meticulously adapted to local environmental conditions. Materials such as baked brick, limestone, river stone, clay, plaster and timber not only minimized environmental impact but also enhanced energy efficiency, thermal stability and structural resilience [11, p. 112].

In seismic regions such as Nakhchivan, the *Momine Khatun* and *Yusuf Kuseir oglu* mausoleums exemplify the mastery of baked brick for both anti-seismic performance and visual aesthetics. A similar approach is evident in the *Ghazan Khan Mausoleum* in Tabriz, where standardized brick dimensions and high-quality mortar contributed to structural longevity [3, p. 93]. On the Absheron Peninsula — notably in the 14th-century *Qarapaltar Piri* shrine in Buzovna — a combination of limestone and clay was employed to counteract temperature fluctuations and humidity, embodying what modern material science refers to as *adaptive material behavior* [7, p. 136].

Traditional spatial configurations also demonstrate sophisticated sustainability logic. The courtyard-centered typology, prevalent across both rural and urban settings, provided microclimatic moderation and social cohesion. Courtyards facilitated shading in summer and wind protection in winter, while the orientation of buildings responded to local climatic forces. In Absheron, houses typically faced south and southeast to maximize passive solar gain, whereas in Tabriz, underground *qanat* cooling systems and thick masonry walls ensured natural temperature regulation [4, p. 174].

Constructive systems formed the technological foundation of durability. The integration of stone and brick masonry, timber seismic bands, and *dry-stone* construction ensured both structural stability and aesthetic rhythm. Domes and arches distributed loads spherically, contributing to exceptional longevity [15, p. 214; 22]. In Shaki architecture, stalactite arches, wooden ceilings, and cornices combined decorative and load-bearing functions. Timber — particularly oak, plane, and elm — acted as a “breathing material,” facilitating natural ventilation and maintaining interior humidity balance [11, p. 114; 23].

These design elements collectively represent not only cultural heritage but also a functional sustainability framework. However, the preservation of this potential requires a systematic, research-based conservation policy. Azerbaijan’s post-independence restoration and conservation initiatives demonstrate a significant shift toward sustainable heritage management. Since the early 2000s, projects conducted under the “Cultural Heritage Preservation Program”, supported by the World Bank, have involved major sites such as the *Palace of the Shirvanshahs* (Baku), *Momine Khatun Mausoleum* (Nakhchivan), *Sheki Khan Palace*, *Ateshgah Temple*, and *Sheikh Babi Complex* [13, p. 120].

The main objective of these projects was not only the restoration of the physical structure, but also the preservation of the monument’s functional and social value. For example, in the Shakikhans’ House, the reconstruction of the 18th-century lifestyle was carried out based on the principle of adaptive reuse. The transformation of the caravanserais in Ganja into hotels and tourism facilities represents a successful example of integrating architectural heritage into social and economic circulation [14, p. 92].

During the conservation works at the Sheikh Babi Complex in the Fuzuli district, measures were taken to improve the chemical and physical durability of materials and to prepare the structure for long-term operation — serving as an example of the technological applications of sustainable architecture [11, p. 128].

The restoration works carried out in regions such as Quba, Qakh, Barda, Salyan, and Balakan demonstrate that the principle of “integral conservation” has taken shape in Azerbaijan. This approach ensures the simultaneous restoration of the constructive, functional and visual layers of architectural heritage.

Thus, the sustainability principles of traditional architecture can be regarded as a methodological basis applicable both in modern restoration practice and in architectural education. Azerbaijan’s experience in this field can be studied and applied as a regional model of sustainable conservation at

the international level.

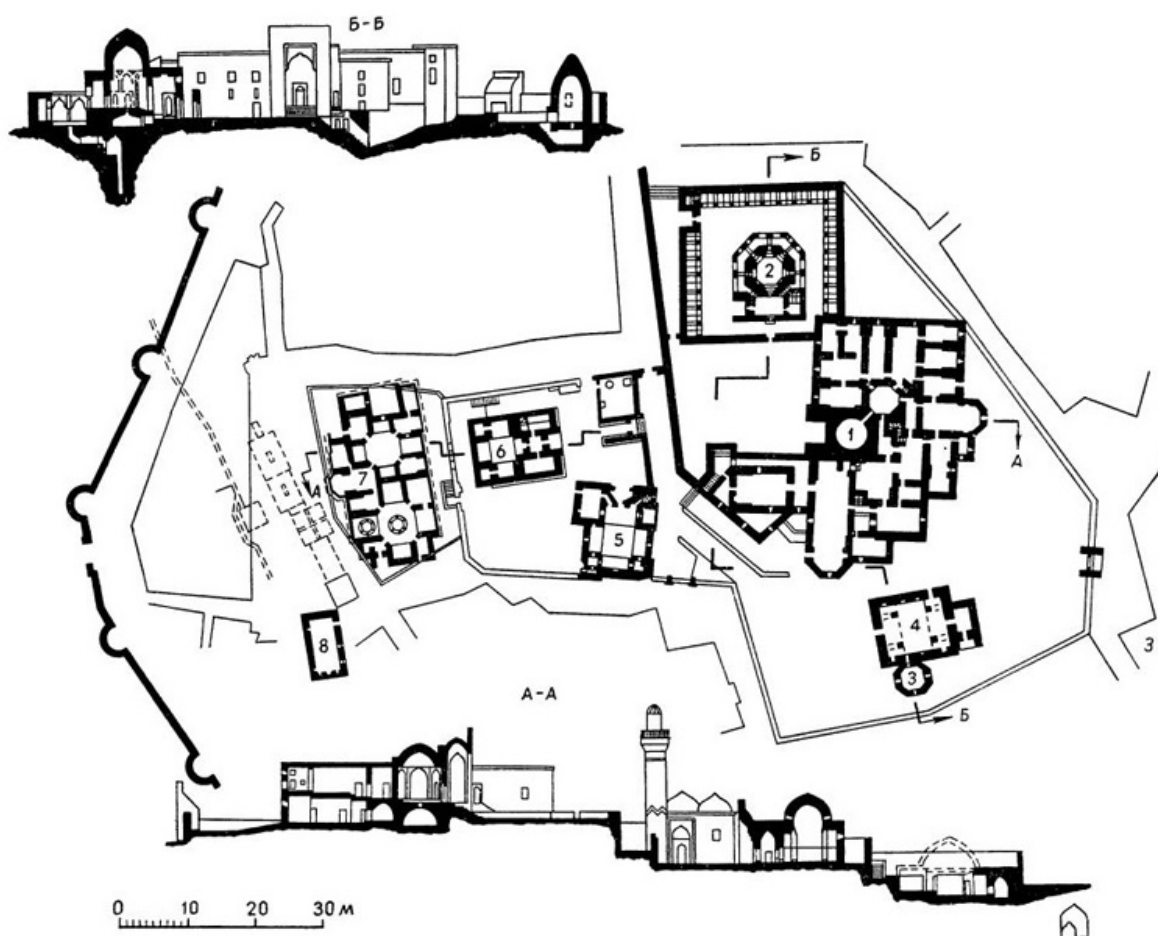


Fig. 2. Baku. Ensemble of the Shirvanshah Palace. General view, axonometry, plan, and sections:
1 — Palace; 2 — Divan-khane; 3 — Mausoleum of Seyid Yahya Bakuvi; 4 — Key-Qubad Mosque; 5 — Palace Mosque; 6 — Mausoleum; 7 — Palace Bathhouse; 8 — Chin Mosque [15]

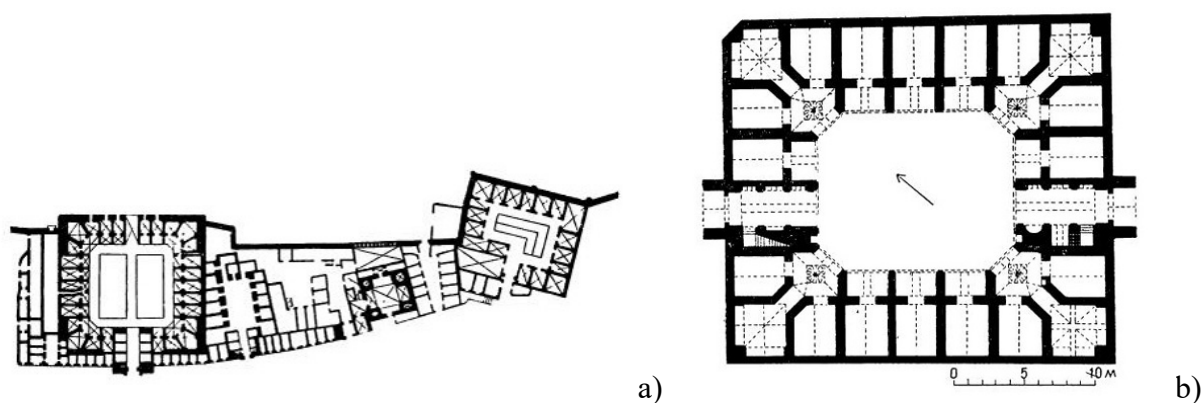


Fig. 3. a — Baku. Commercial complex. Plan of the 19th century.
b — Baku. Icherisheher (Old City). Two-story caravanserai. Plan of the first floor [14]

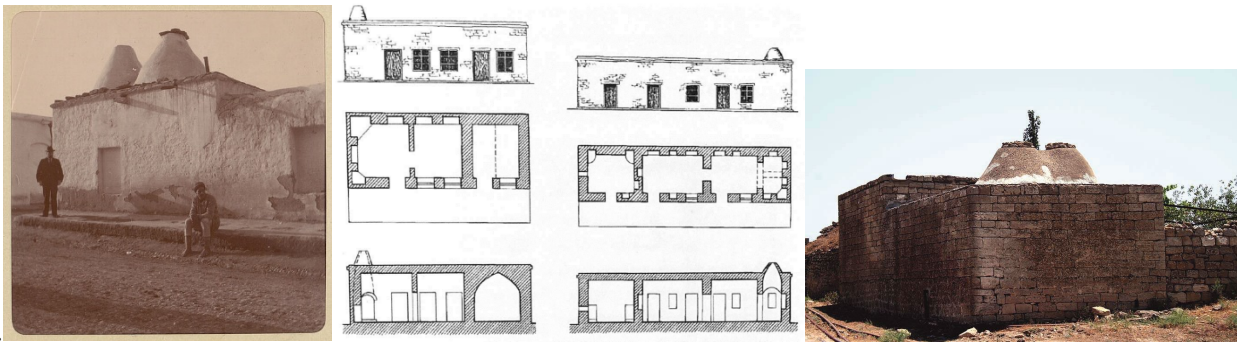


Fig. 4. Residential houses in Absheron (according to A. Mekhtiyev)[15]:

a) Absheron house types, 19th century. Facade, plan, section;

b) Structural scheme of a traditional house wall — thick stone wall (50–70 cm), interior clay plaster layer, wooden ceiling beams, and earthen roof covering. (The diagram illustrates the constructive composition of the wall — the thermal mass of the stone and the insulating function of the earthen layer)

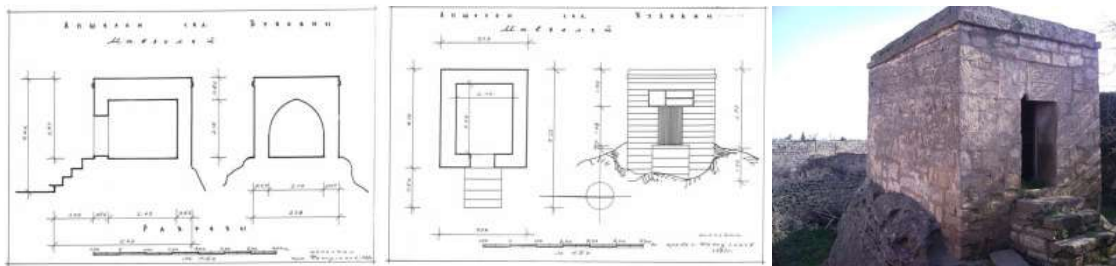


Fig. 5. The domed plan of the Qarapaltar Piri sanctuary in Buzovna (Absheron). 14th century (by Sh. Fatullayev) [13]



Fig. 6. Khinalig residential houses. Courtyard-based house plans adapted to the mountain climate. (The diagram may show the placement of rooms around the courtyard, air circulation directions, solar angles, and shading zones) [13]

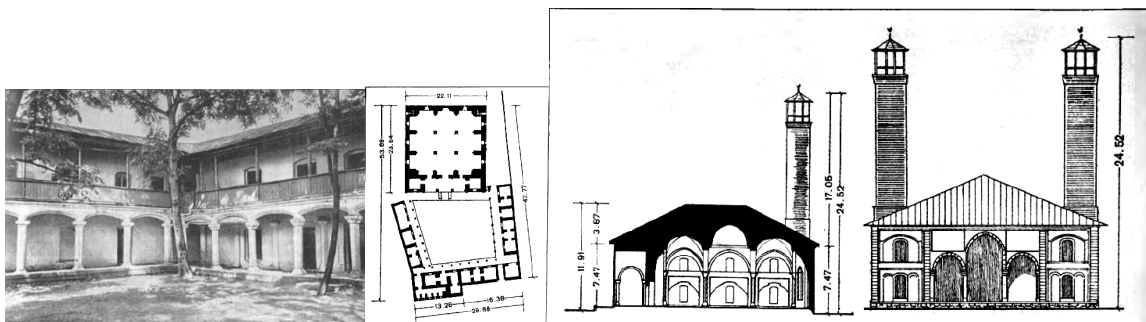


Fig. 7. Shusha. Lower Mosque of Govhar Agha. Facade, section, and plan. Architect K.S. Garabagi, 1874–1875.[13]

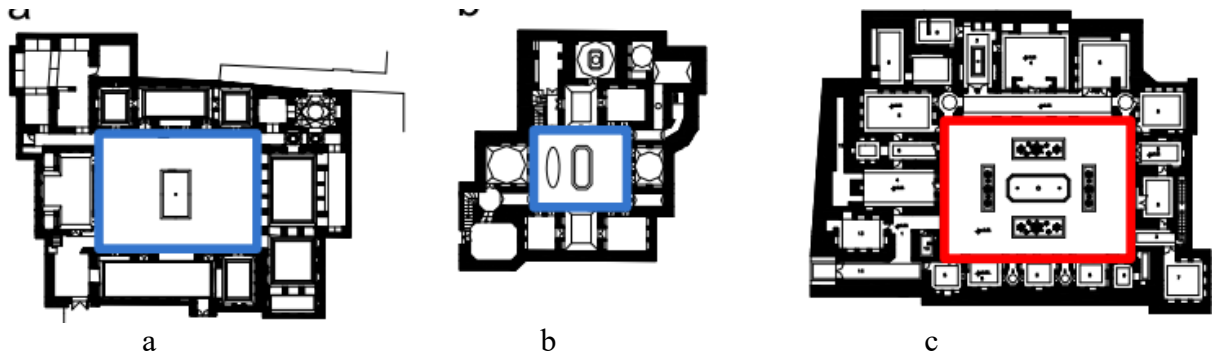


Fig. 8. Traditional Iranian courtyard houses: (a) Lotfali Khan House, Kerman; (b) Azimi House, Kerman; (c) Movahedi House, Kerman; [26]

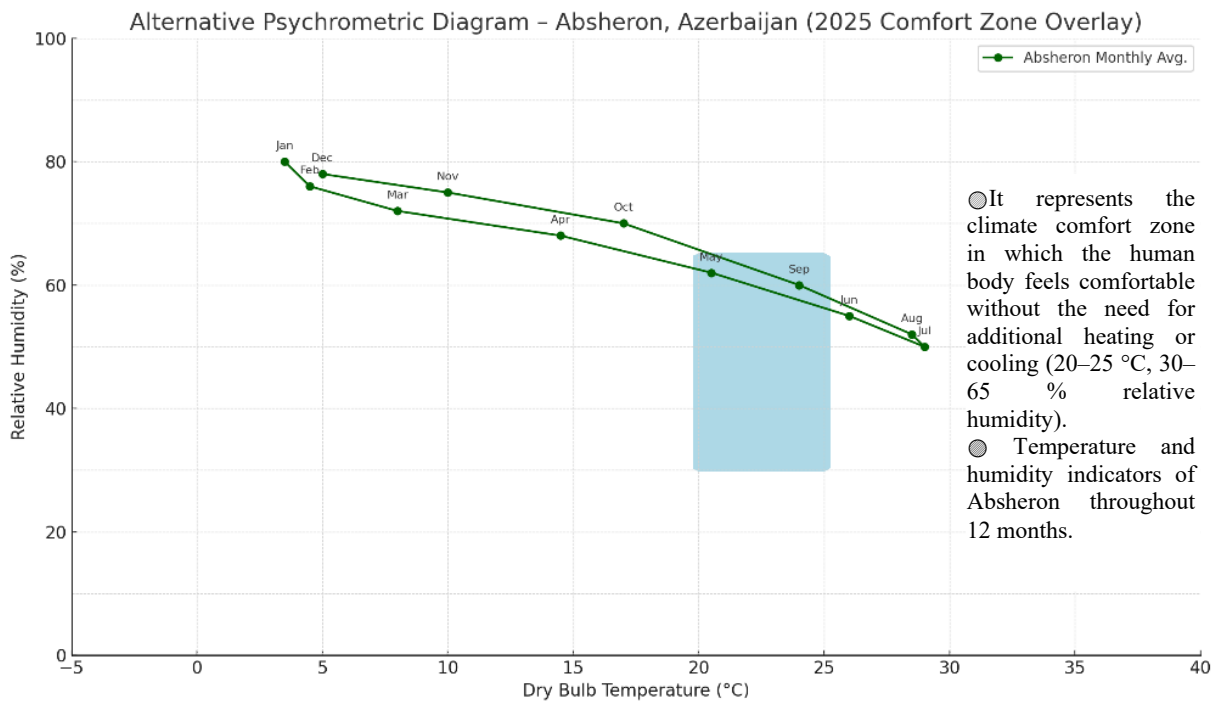


Fig. 9. Alternative psychrometric chart for the Absheron (Azerbaijan) region showing the 2025 California Comfort Model comfort zone (blue area)

The climatic analysis demonstrates that the characteristic weather conditions of the Absheron Peninsula directly affect architectural planning throughout the year. From January to March and November to December, the climate is cold and humid, corresponding to conditions located below and to the left of the comfort zone. From June to August, the weather becomes very hot and relatively dry, i.e., the temperature is above the comfort zone. The most optimal conditions are observed in April, May and September, which are the closest months to the comfort zone.

Based on this analysis, the climate diagram serves as a decision-making tool for architectural design and energy-efficient construction. It enables the planning of key architectural measures such as:

- Defining passive heat-gain zones;
- Designing solar shading systems;
- Planning open spaces for natural ventilation.

The diagram also visually reflects the climate-adaptive planning principles of traditional Absheron houses, which were designed for cold-dry climatic conditions and demonstrate energy-efficient structural solutions.

A similar approach is also emphasized in contemporary scientific research: Starzyk et al. [24] examined the impact of climate adaptation and material selection on the energy performance of zero-carbon timber structures, while Wang and Chiou [25] demonstrated the relationship between the

spatial configuration of traditional residential forms and the principles of sustainable development. In this context, a thermal loss analysis of a traditional Absheron house reveals the following patterns:

Table 2. Analysis and effect of the zones

Zone	Analysis and effect
North Wall	Directly exposed to strong “Khazri” winds — highest heat loss
East Wall	Receives morning sun but remains cold — moderate to high loss
South Wall	Gains solar heat during the day but loses it at night — moderate loss
West Wall	Relatively shielded from sunlight — minimal heat loss
Windows	North-facing windows — very high loss; south-facing windows — potential for solar gain

Architectural implications:

- North walls should be thickened and insulated, with fewer openings.
- South-facing facades can include larger windows integrated with shading systems to capture passive solar energy.

- Material selection and moisture protection remain priorities for maximizing energy efficiency.

This approach bridges the climate-adaptive principles of traditional architecture with modern energy-efficient design, offering a practical foundation for sustainable architecture [23; 24].

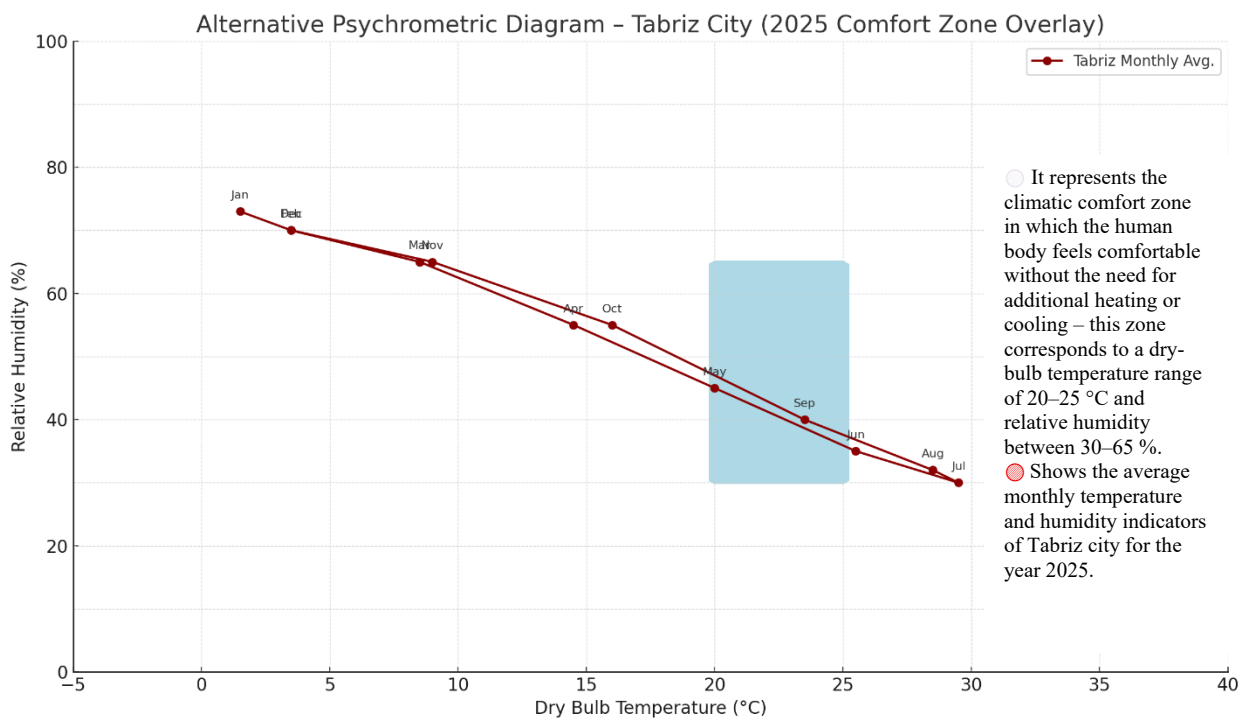


Fig. 10. Alternative psychrometric chart for Tabriz — the transparent background indicates the comfort zone, while the monthly climatic points (temperature + humidity) are marked by dots with corresponding labels

The cold-dry climate type (BSk) of Tabriz city is characterized by significant seasonal temperature differences and low humidity levels. Analyses based on the 2025 California Comfort Model show that the annual climate trajectory of Tabriz partially overlaps with the comfort zone: comfortable conditions are observed in May and September, while during the winter (January–March) and summer (July–August) months, the indicators deviate from this zone.

The main advantage of this diagram is that the annual climate trajectory can be visually tracked, where the blue background represents the *thermal comfort zone*, the area in which the human body

maintains an optimal heat balance. Thus, this model provides a scientific foundation for decision-making in architectural planning and energy-efficient passive design.

In Tabriz, summers are hot and dry, while winters are cold. Traditional Tabriz houses respond to these climatic variations through passive adaptation techniques. Northern rooms are mainly used in summer because they offer cool and shaded conditions, while southern rooms are designed for winter habitation, maximizing solar gain. The courtyard structure—the central yard— helps maintain the building's climatic balance, providing cooling during summer and storing radiant heat in winter.

Such architectural solutions, formed on the basis of local wisdom, confirm the importance of the “*green construction and local wisdom integration*” approach highlighted in modern research [27]. In terms of layout, Tabriz houses are characterized by a compact structure, which reduces heat loss. Their thick walls moderate day–night temperature fluctuations, while the courtyard promotes airflow and creates a microclimate. The building orientation and high courtyard walls act as barriers against cold northern winds.

Traditional materials exhibit energy behavior compatible with the local climate. Mudbrick and stone walls have high thermal mass, retaining heat at night and providing coolness during the day. Unbaked brick and stone floors maintain thermal contact with the ground, ensuring temperature stability. Wooden beams and plaster coatings help regulate humidity and allow surfaces to breathe. Small wooden lattice windows transmit light while reducing heat loss. Pools and fountains in the courtyard increase humidity through evaporation, contributing to cooling during summer.

As noted by Ayoobi et al. [29], these characteristics form an essential foundation for integrating vernacular and sustainable architectural principles within a modern holistic building design framework. Thick double walls enhance thermal insulation, and upper windows enable the release of warm air. The separation of summer and winter rooms contributes to seasonal energy efficiency and extends the period of thermal comfort.

In traditional Tabriz houses, solar gain, shading elements, natural airflow, evaporative cooling, and high thermal-mass materials play a central role. Southern rooms provide passive solar heating in winter, while porches and overhangs block solar radiation in summer. Courtyards and vaulted passages ensure natural ventilation, and water features and plants increase humidity. These methods provide energy savings without reliance on technology, creating living environments in harmony with the climate. Such characteristics serve as indicators of both ecological and social sustainability [28].

Courtyard-based housing plans in various Iranian cities such as Kerman, Isfahan and Tabriz, are based on similar principles. In these designs, the central courtyard functions as a primary microclimatic regulator. Pools and vegetation provide cooling through evaporation, while the orientation of rooms toward the south maximizes solar gain in winter. The northern “taxtabaz” rooms are used as cool spaces during summer.

Natural ventilation is achieved through rooms opening into the courtyard, while corridors and semi-open balconies enhance air circulation. A modular harmony is maintained between the courtyard's size and the surrounding rooms, preserving both energy balance and social functionality. In contemporary research, these traditional architectural models are regarded as valuable examples for maintaining aesthetic, functional and durability values [30].

In conclusion, traditional architecture of Tabriz developed passive climate strategies that align with modern comfort zone criteria centuries ago, providing energy efficiency without technology. This system establishes a living environment in harmony with the climate, while reflecting a sustainable architectural model consistent with social and cultural values.

A comparative analysis of traditional architectural systems reveals that although the architectural practices of both Tabriz and Absheron regions have developed in response to similar climatic conditions, cold–dry and semi-arid climates, the applied architectural solutions and passive design techniques have evolved in different directions. These differences are closely related to each region's geographical location, wind regime, humidity level and socio-cultural context.

The architecture of Tabriz is primarily adapted to a dry continental climate, while Absheron reflects the characteristics of a semi-arid climate influenced by the sea. Both regions share common design principles such as courtyard-centered planning, thick wall structures, passive solar gain, and

orientation in harmony with nature. However, the methods of implementation and construction details differ significantly.

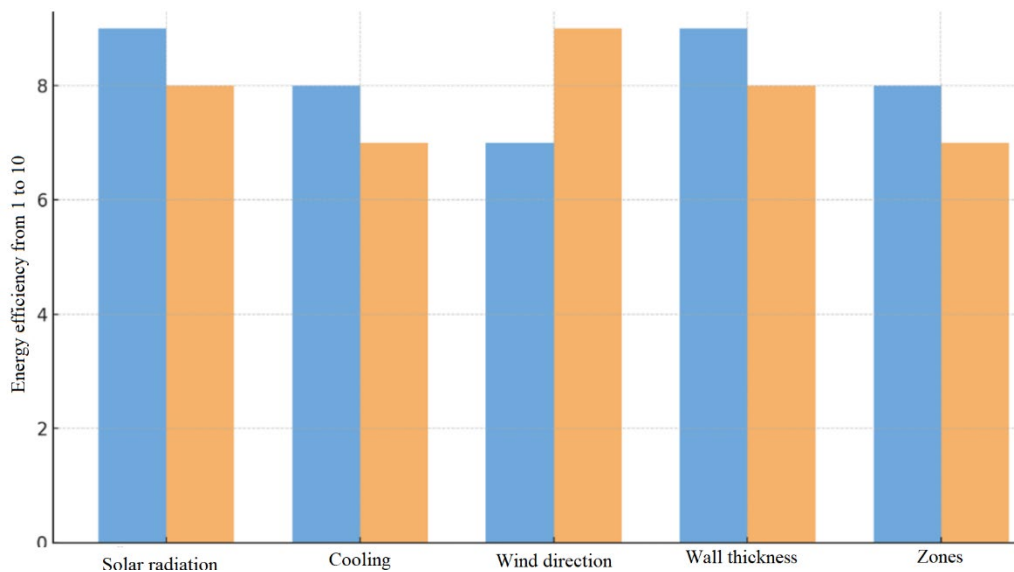


Fig. 11. Comparative Analysis of Tabriz and Absheron Architecture
■ - Tabriz, ■ - Absheron

The comparative analysis indicates that solar gain and thermal mass are more effectively preserved in Tabriz architecture, whereas wind direction utilization and ventilation systems operate more efficiently in Absheron. Although both regions show similar results in terms of wall thickness and spatial zoning, their climatic response strategies are based on distinct priorities.

The Passive Strategy Efficiency Diagram visually demonstrates these differences across five main principles: solar gain, cooling, wind direction, wall thickness and zoning. Tabriz dwellings emphasize heat retention and solar energy gain, while Absheron houses focus on air circulation and wind optimization. This indicates that the two regional models complement each other in terms of achieving climatic balance.

The following comparative assessment describes the effectiveness of the five key passive strategies: solar gain, cooling, wind orientation, wall thickness, and spatial zoning in relation to their climatic adaptability in the traditional architecture of Tabriz and Absheron (Table 4).

Table 4. Passive strategies in the traditional architecture of Tabriz and Absheron

Strategy	Tabriz	Absheron
Solar Gain	South-oriented rooms and thick walls ensure high levels of solar energy collection, maintaining indoor warmth in winter.	South-facing layouts are present but less effective due to humidity and wind exposure.
Cooling	Central courtyards, pools, and shaded areas provide evaporative cooling and passive ventilation.	Cooling relies on cross-ventilation and open yards; however, high humidity slightly limits efficiency.
Wind Orientation	Buildings are arranged to block cold northern winds.	Wind patterns (Khazri and Gilavar) are central to building orientation and ventilation design.
Wall Thickness	Thick adobe and stone walls maintain stable indoor temperatures and minimize diurnal variation.	Thick brick and limestone walls serve a similar purpose but are adapted to milder maritime conditions.
Spatial Zoning	Seasonal room use: south rooms in winter, north rooms in summer ensures flexible	Zoning is present but less pronounced due to smaller climatic fluctuations.

	comfort.	
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This comparison demonstrates that both regions preserve local knowledge and material technologies within climate-adapted and energy-efficient systems. As emphasized by Dişli and Arslan [32], this represents a typical example of how traditional knowledge systems contribute to sustainable urban development.

Based on these findings, a Transfer Model for Contemporary Architecture can be developed. This model proposes the integration of principles tested in traditional architecture with modern architectural technologies. Traditional functions can be reinterpreted and revitalized through the use of modern materials, energy systems, and smart technologies, ensuring the continuity of vernacular wisdom within sustainable design practices.

Traditional Function	Modern Adaptation
Central courtyard	Light atrium, green courtyard and natural ventilation core
Thick earthen walls	Insulated “sandwich” walls (brick + EPS + gypsum)
Passive shading (arches, iwans)	Brise-soleil systems, solar-panel shading devices
South–north spatial zoning	Smart seasonal zones for energy-efficient use
Water-based evaporative cooling	Green facades and water-curtain bioclimatic cooling systems

This approach holds strategic importance both for the preservation of cultural heritage and the advancement of sustainable urban development. As noted by Velibeyoğlu and Sedes [31], *symbiotic architecture*: that is, the integration of historical structures with modern technologies, transforms cultural heritage while shaping a sustainable future. In this context, the architectural traditions of Tabriz and Absheron establish a symbiotic relationship between the architectural legacy of the past and the ecological approaches of the future.

Thus, the traditional architecture of Tabriz and Absheron embodies not only historical and aesthetic value, but also serves as a scientific foundation for modern energy-efficient and climate-responsive design. Through the reapplication of these principles, it is possible to create sustainable, ecologically conscious, and socially balanced contemporary living environments. In this sense, traditional architecture represents not merely the experience of the past, but also a localized model for the sustainable design concepts of the future.

4.Conclusion and recommendations. Traditional architecture is not merely a historical heritage of aesthetic value, but a knowledge system that constitutes both the scientific and practical foundations of contemporary sustainable design. A comparative analysis of architectural examples from different regions of Azerbaijan, alongside similar structures in Anatolia and Tabriz—reveals that these architectural forms represent naturally adaptive systems, fully integrated with climate, topography, and social structure. This approach ensured a synthesis of local material use, passive energy strategies, anti-seismic construction techniques and socio-cultural coherence [10, 4]. The architecture of Absheron with its limestone masonry, thick walls, and domed coverings; Nakhchivan structures featuring fired brick and seismically flexible frameworks; and the Shaki–Zaqatala school distinguished by timber, stone, and stalactite arch systems each present distinct models of resilience. Tabriz architecture complements these examples by demonstrating the thermal mass and climatic endurance of fired brick, while Anatolian architecture emphasizes courtyard-centered planning and passive ventilation systems [16, 8]. The comparative study of these regions shows that, despite climatic differences, their traditional forms share a common foundational logic—construction based on local resources, natural ventilation and social adaptability. In the post-independence period, Azerbaijan’s restoration and conservation initiatives such as the Palace of the Shirvanshahs, Shaki Khan’s Palace, Momine Khatun Mausoleum and the Ateshgah Complex illustrate how these traditions have been integrated into modern architectural policy and economic systems. The projects implemented by *Azərbaypa* Scientific-Research Institute and supported by the World Bank’s “Cultural Heritage Preservation” program have demonstrated that architectural heritage conservation is not merely a technical process, but also involves social and functional revitalization [11].

Key Findings

1. The constructive and planning principles of traditional architecture can be directly transferred into modern bioclimatic design and green architecture strategies.
2. The architectural schools of Azerbaijan and Tabriz present regional models of sustainability, maintaining the relationship between local materials and diverse energy balances across climatic zones.
3. Restoration policies should focus not only on technical stability, but also on the integration of heritage sites into cultural, social, and economic circulation (e.g., tourism, education, and public functions).
4. The adaptation of traditional building materials as brick, limestone and wood to modern production systems can promote energy efficiency and reduce carbon emissions [7, 6].
5. The teaching and application of these knowledge systems within architectural education and design practice are essential for fostering interdisciplinary ecological approaches.

Recommendations

- Passive energy systems and climate-responsive material choices derived from traditional architecture should be integrated into modern design standards.
- A “Sustainable Design Atlas” based on regional characteristics should be developed as a practical guide for architects and engineers.
- Policies promoting the reuse and adaptive use of protected buildings with new functions should be institutionalized at the state level.
- The eco-friendly reproduction of traditional materials and their linkage to local economies should be defined as a priority direction.
- Conservation and urban planning policies must be reinforced with new climate-responsive durability standards to ensure the longevity of architectural heritage.

In conclusion, the traditional architectures of Azerbaijan, Tabriz and Anatolia demonstrate that the architecture of a sustainable future is achievable through the reinterpretation of the codes of the past. This architectural legacy represents not only a cultural value, but also a scientific model of ecological stability, social harmony, and material circulation, defining the future trajectory of contemporary sustainable architecture.

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Received: 07/09/2025 Accepted: 16/11/2025 Published: 30/12/2025

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